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# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**INTEGRATION AND ENVIRONMENTAL QUALIFICATION TESTING OF SPACECRAFT STRUCTURES IN SUPPORT OF THE NAVAL POSTGRADUATE SCHOOL CUBESAT LAUNCHER PROGRAM**

by

Adam Charles DeJesus

June 2009

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| Thesis Advisor: | James H. Newman |
| Second Reader: | Daniel Sakoda |

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The purpose of this thesis is to document the process of designing, constructing, and testing a qualification article in support of the NPS CubeSat Launcher (NPSCuL) project, in the NPSCuL-Lite configuration. NPSCuL-Lite is designed to launch a significant volume of CubeSats into orbit in a single launch. The NPSCuL-Lite will be a secondary payload on U.S. launch vehicles, and will be attached to the launch vehicle via the EELV Secondary Payload Adapter (ESPA), the Atlas-Centaur Aft Bulkhead Carrier (ABC), or other ESPA-compatible launch vehicle interfaces. NPSCuL-Lite will host CubeSats in up to eight Poly Picosatellite Orbital Deployers (P-PODs) developed by the California Polytechnic State University (Cal-Poly). To meet launch requirements, the designer must prove that NPSCuL-Lite and its subsystems (the P-PODs and CubeSats) will operate properly in space, and will not interfere with the launch vehicle, the primary payload, or other secondary payloads. To this end, qualification testing will ensure NPSCuL-Lite can survive ground transport, launch, and CubeSat deployment. Additionally, the initial development of procedures and equipment necessary for ground handling and launch vehicle integration are addressed.

| **14. SUBJECT TERMS** Atlas, ABC, CubeSat, ESPA, EELV, NPSCuL, NPSCuL-Lite,, Picosatellite, Satellite, Space, Spacecraft, Structure, Launcher, Launch, ABC, Centaur, Qualification, Testing, Integration, Vibration | | | **15. NUMBER OF PAGES**<br>119<br>**16. PRICE CODE** |
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# INTEGRATION AND ENVIRONMENTAL QUALIFICATION TESTING OF SPACECRAFT STRUCTURES IN SUPPORT OF THE NAVAL POSTGRADUATE SCHOOL CUBESAT LAUNCHER PROGRAM

Adam C. DeJesus
Lieutenant Commander, United States Navy
B.A., St. John's University, 1996

Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS**

from the

**NAVAL POSTGRADUATE SCHOOL**
**June 2009**

Author: Adam C. DeJesus, LCDR, USN

Approved by: James H. Newman
Thesis Advisor

Daniel Sakoda, Research Associate
Second Reader

Rudolf Panholzer
Chair, Space Systems Academic Group
Graduate School of Engineering and Applied Sciences

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## ABSTRACT

The purpose of this thesis is to document the process of designing, constructing, and testing a qualification article in support of the NPS CubeSat Launcher (NPSCuL) project, in the NPSCuL-Lite configuration. NPSCuL-Lite is designed to launch a significant volume of CubeSats into orbit in a single launch. The NPSCuL-Lite will be a secondary payload on U.S. launch vehicles, and will be attached to the launch vehicle via the EELV Secondary Payload Adapter (ESPA), the Atlas-Centaur Aft Bulkhead Carrier (ABC), or other ESPA-compatible launch vehicle interfaces. NPSCuL-Lite will host CubeSats in up to eight Poly Picosatellite Orbital Deployers (P-PODs) developed by the California Polytechnic State University (Cal-Poly). To meet launch requirements, the designer must prove that NPSCuL-Lite and its subsystems (the P-PODs and CubeSats) will operate properly in space, and will not interfere with the launch vehicle, the primary payload, or other secondary payloads. To this end, qualification testing will ensure NPSCuL-Lite can survive ground transport, launch, and CubeSat deployment. Additionally, the initial development of procedures and equipment necessary for ground handling and launch vehicle integration are addressed.

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Finally, I could not have completed this work without the influence and encouragement of Dr. Nancy Haegel, PhD., Physics Department, Naval Postgraduate School. She patiently taught me the basics and instilled in me an intense desire to understand the physical universe.

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# I. INTRODUCTION AND BACKGROUND

## A. CUBESATS AND P-PODS

### 1. What is a CubeSat?

The term “CubeSat” describes any nanosatellite designed in compliance with the particular CubeSat design specification promulgated by California Polytechnic State University (Cal Poly).[1] The basic CubeSat is a 10cm cube with a mass of approximately 1 kg, which contains all required subsystems for a particular space mission including a payload, on-board computer, communications suite, attitude determination and control system (ADCS), electrical power system, etc. The CubeSat form factor of 10 cm x 10 cm x 10 cm is referred to as 1U, or a 1-unit CubeSat. Common variations of the standard 1U size include 2U (20 cm x 10 cm x 10 cm) and 3U (30 cm x 20 cm x 10 cm) CubeSats. Other sizes may be developed in the future; among these, significant interest has been shown in the 5U (50 cm x 10 cm x 10 cm), and the 6U or “six-pack” (30 cm x 20 cm x10 cm) form factors. In spite of any similarity in shape and size, a nanosatellite that does not conform to the CubeSat design specification cannot be accurately called a CubeSat.

According to the CubeSat design specification, “The primary mission of the CubeSat Program is to provide access to space for small payloads.”[2] This provides a number of advantages for the satellite developer. Compared to larger satellites, CubeSats have lower development, testing, and construction costs. The CubeSat standard also enables decreased design and development timelines. Finally, the deployment mechanism designed by Cal Poly simplifies the integration requirements for launch services.

1 Wenschel Lan et al., “Cubesat Design Specification, Revision 11.” California Polytechnic State University, San Luis Obispo, 2008.

2 Ibid.

### 2. What is a P-POD?

The Poly Picosatellite Orbital Deployer (P-POD) provides a standardized deployment mechanism for CubeSats.[3] P-PODs are integrated as secondary payloads on a large variety of launch vehicles. The current standard P-POD capacity is 3U; that is, a standard P-POD may deploy three 1U CubeSats or one 3U CubeSat, or a 1U and a 2U CubeSat. The potential exists to expand the P-POD to a 5U or 6U capacity, to accommodate the larger CubeSats described above; however, these deployers are still in the concept stage of development. The P-POD operates in the following manner: the P-POD door maintains pressure against the enclosed CubeSats which, in turn, maintain pressure against a deployment spring until the deployment signal is received. Upon receipt of a standard deployment signal from the launch vehicle, a non-explosive actuator (NEA) releases a bolt that allows the P-POD door to open. This allows the deployment spring to push the enclosed CubeSats out of the P-POD. A single P-POD may therefore deploy one, two, or three CubeSats when a single deployment signal is received. The deployment may take place while the launch vehicle is in powered flight (as in two DNEPR launches) or while the launch vehicle is on-orbit. One launch vehicle may carry several P-PODs depending on available volume and mass and other integration requirements.

The P-POD has a highly successful flight history.[4] While launch vehicle failures and failures aboard individual CubeSats have prevented some CubeSats from being successful, the P-POD has never failed to deploy the CubeSats upon receipt of the deployment signal. This heritage makes the P-POD an ideal subsystem for NPSCuL-Lite.

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3 Wenschel Lan, "Poly Picosatellite Orbital Deployer Mark III ICD," California Polytechnic State University, San Luis Obispo, 2007.

4 Alexander Chin et al., "The CubeSat: The Picosatellite Standard for Research and Education," American Institute of Aeronautics and Astronautics, AIAA Space 2008 Conference and Exhibition, 2008.

### 3. Space Access Challenges to the CubeSat Community

In less than ten years since establishment of the CubeSat standard. the community of CubeSat developers has grown to over 100 organizations including academic, research, commercial, and government enterprises. But only 30 or so have ever launched, and this is due to several policy factors. Almost all CubeSats to date have been launched from sites outside the continental United States, because integration and launch on foreign launch vehicles tends to be easier and cheaper than on U.S. launch providers. Domestically-produced experimental payloads and equipment, which are attractive to CubeSat developers because of reduced size, mass, or power requirements, are often difficult to transport to foreign countries due to U.S. International Traffic in Arms Regulations (ITAR), even if the travel is only for the purpose of launching on a foreign rocket. Finally, U.S. launch providers have not embraced CubeSats as viable secondary payloads—this may be for many reasons including lack of capacity, risk intolerance, and the perception that CubeSats offer limited benefit in terms of mission utility. The Naval Postgraduate School CubeSat Launcher (NPSCuL) program was conceived as a way to mitigate these challenges to space access for CubeSats.[5] Launch of a CubeSat aboard US launch vehicles from US launch facilities would allow CubeSats of a sensitive nature (due to security classification or advanced technology) to be developed, tested, and flown without the management burden of ITAR. Integration of P-PODs on launch vehicles to-date has never been standardized; NPSCuL was designed to provide a standard, repeatable integration process, with a physical structure that can easily conform to several secondary payload carrier concepts while simultaneously reducing risk to the primary payload. The NPSCuL concept further addresses the fact that one or two individual P-PODs would not make good use of the excess weight capacity of US launch vehicles; this same excess

5 James H. Newman, Daniel Sakoda, and Rudolph Panholzer, “CubeSat Launchers, ESPA-rings, and Education at the Naval Postgraduate School,” (presentation, 21st Annual AIAA/USU Conference on Small Satellites, August 2007).

capacity is what drove the Space Test Program to develop the Enhanced Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) in the first place. By packaging a larger number of P-PODs in a single unit compatible with ESPA, NPSCuL will change the cost-benefit ratio associated with launching CubeSats as secondary payloads.

## B. NPSCUL/NPSCUL-LITE PROGRAM HISTORY TO DATE

### 1. NPSCuL Development

Felix Roßberg and Matthew Crook demonstrated the feasibility of integrating multiple P-PODs in a single structure that could fit within the ESPA-dictated mass and volume constraints. In 2007, Felix Roßberg performed in-depth analysis of various design possibilities to maximize the payload capacity of NPSCuL while minimizing weight and complexity.[6] The 2007 Department of Defense (DoD) Space Experiments Review Board (SERB), which ranks military science and technology experiments on behalf of the Space Test Program, ranked NPSCuL 45 of 51 projects, due largely to the efforts of Felix Roßberg and the NPS Space Systems Academic Group (SSAG). In 2008, Matthew Crook took a critical look at the challenges of designing, building, and integrating NPSCuL, with payloads from a variety of sources, and determined that such a device would benefit the space community as a whole.[7] He also created a functional, one-half-scale model of Roßberg's NPSCuL (D-structure) design concept, and presented it to the 2008 DoD SERB where the project ranked 36 of 62 projects. The efforts of Roßberg and Crook were critical to the project and their contributions are well documented. The next section discusses how the concept changed when the first flight opportunity presented itself.

6 Felix Roßberg, "Structural Design of a NPS CubeSat Launcher" (Master's thesis, Naval Postgraduate School, 2008).

7 Matthew Crook, "NPS CubeSat Launcher Design, Process and Requirements," Master's thesis, Naval Postgraduate School, 2009.

### 2. NPSCuL-Lite and the First Launch Opportunity

The NPSCuL concept continued to gain momentum throughout 2008. At several conferences, including the annual AIAA/USU Conference on Small Satellites, it garnered ever-increasing interest from academic, commercial, and government CubeSat developers and launch providers alike. In August 2008, the National Reconnaissance Office (NRO) expressed interest in funding the NPSCuL project, with the intent of launching several government payloads in 2010 using a heretofore unknown secondary payload adapter. Subsequently, the sponsor provided a modest grant of $39,000 to develop the concept and produce test hardware in support of a 2010 launch on the developmental payload adapter, as described below.

The Aft Bulkhead Carrier (ABC) was conceived by the United Launch Alliance in response to a design change to the Centaur upper stage of the Atlas rocket family. The Centaur has been in use since the 1960s and has seen many design changes over the years; the latest modification involved the removal of a helium tank that was formerly mounted behind the main fuel tanks. This left a small space that could be used to carry a secondary payload. The ABC requirements, however, are much more restrictive than those of ESPA-compatible payloads. The available volume and mass are smaller, the launch environments (vibration and thermal) are more severe, and the ABC is a green, under-developed payload adapter with many unknowns.

To meet the requirements of the Centaur ABC, the NPSCuL Team made significant changes to the original design. The structural mass was cut almost in half, and the volume was similarly reduced. Since the new version would only carry about half the CubeSat capacity of NPSCuL, it was dubbed NPSCuL-Lite. It could carry 24U of CubeSats in eight P-PODs and meet the mass and volume requirements of the Centaur ABC while maintaining full compatibility with ESPA.

The structure would also carry a flight electronics unit, called a “sequencer,” that provided eight pre-programmed deployment signals to eight P-PODs with electrical power received from the Centaur.

The first launch opportunity for NPSCuL-Lite will be as part of the National Reconnaissance Office’s Advanced Science and Technology (AS&T) Demonstration and Maturation Satellite, or ADaMSat. It will launch along with the NROL–41 mission, which is slated to carry a classified U.S. Government satellite as the primary payload on an Atlas V rocket from Vandenberg AFB. This is also the first launch opportunity for the modified Centaur upper stage with the ABC adapter. The launch date has been tentatively set for August 2010, and requires the secondary payload to be fully integrated and delivered to the launch site about four months prior to launch. Total time available to develop, test, and deliver NPSCuL-Lite, from acceptance of the proposal to delivery to the launch site, was 18 months (October 2008 to February 2010). Table 1 outlines the major schedule milestones and the timeline of deliverables required for manifest and launch on the NROL–41 flight.

From the moment the NPSCuL-Lite test program began, time management was critical for success of the project. No matter how simple a spacecraft structure may be, it must still pass through all the “wickets” required for space qualification and verification; the detailed design, testing, and documentation of every aspect of spacecraft structures takes a certain minimum amount of time. The use of student labor reduces cost but adds a certain degree of risk that can only be mitigated by taking the time to develop a level of expertise in every major area of the design.

The team consisted of a program manager, a structure designer, an integration and test manager, and a sequencer engineer. All were assisted by the engineers of the NPS SSAG who brought their prior experience to bear on every aspect of the project. The program manager handled the budget, schedule, performance requirements, and materiel procurement, in addition to being the senior point-of-contact for all other coordinating agencies. The

structure designer handled the mass properties, physical layout, and detailed design of NPSCuL-Lite, and assisted with production of the finite element model. The sequencer engineer determined the sequencer system requirements,

| Action | Responsible Party | Completed/Due | Notes |
|---|---|---|---|
| **NPSCuL Team Activity Schedule** | | | |
| **Proposal** | NPS to NRO | 7-Aug-08 | Completed for qualification unit only |
| **System Design** | NPS-Structure Design | 5-Aug-09 | |
| Structural Design | NPS-Structure Design | 13-Apr-09 | completed |
| Complete Drawings | NPS-Structure Design | 10-Mar-09 | completed |
| Structural Modeling | NPS-Structure Design | 13-Apr-09 | completed |
| Develop Mass Budget | NPS-Structure Design | 13-Mar-09 | completed |
| Sequencer Design | ULA (via third party) | 8-May-09 | |
| **Build Qualification Unit** | NPS-Structure Design | 15-Apr-09 | delayed by mass model testing and production timelines |
| Build Sequencer Mass Model | NPS-Electronics | 6-Apr-09 | completed |
| Build P-POD Mass Models | NPS-Integration & Test | 13-Mar-09 | delayed by Mass Model Testing |
| Integrate Qualification Unit | NPS-Integration & Test | 15-Apr-09 | delayed by mass model testing and production timelines |
| **Develop Test Documents** | NPS-Integration & Test | 27-Mar-09 | delayed by lack of ULA environment input |
| **Test Qualification Unit** | NPS-Integration & Test | 5-May-09 | delayed by production timelines |
| **Critical Design Review (CDR)** | **NPS** | **5-Jun-09** | |
| **Build Flight Unit** | NPS-Structure Design | 23-Jun-09 | |
| **Flight Unit Acceptance Testing** | NPS-Integration & Test | 20-Aug-09 | |
| **Flight Readiness Review** | NRO | 24-Aug-09 | |
| **ABC/NROL-41 Integration Required Item Timeline** | | | |
| Final Design Loads Cycle (FDLC) FEM Model | NPS-Structure Design | 1-Feb-09 | met with limited fidelity due to payload unknowns |
| Verification Loads Cycle (VLC) FEM Model | NPS-Structure Design | 1-Mar-09 | met with limited fidelity due to payload unknowns |
| CAD Model - Update | NPS-Structure Design | 1-Jun-09 | |
| CAD Model - Final | NPS-Structure Design | 3-May-10 | |
| Mission Orientation Briefing Input | Mission Integrator (TBD) | 17-Jun-09 | |
| Secondary Payload MSPSP - Preliminary | NPS-Program Manager | 17-Aug-09 | |
| Thermal Model - TMM & GMM | NPS-Structure Design | 2-Mar-09 | completed |
| NPS ENV Test Plan | NPS-Integration & Test | 1-Jun-09 | completed |
| NPS ENV Test Results | NPS-Integration & Test | 1-Feb-10 | reference qualification test results |
| NPS EEDs/NEA EMC Analysis | ULA (via third party) | 22-Jan-10 | |
| Final NPS MSPSP | Mission Integrator (TBD) | 4-Jan-10 | |
| Integrated SP/LV Procedure Inputs | Mission Integrator (TBD) | 1-Jan-10 | |
| Final Target Specification | NRO | 1-Oct-09 | |
| Final NPS Mass Properties | Mission Integrator (TBD) | 20-May-10 | |
| Volume/Envelope Simulator | Mission Integrator (TBD) | 15-Jan-10 | for Gimbal Test & Pathfinder |
| Connectors - Sequencer Harness I/F | NPS-Electronics | 31-Mar-10 | |
| Sequencer EDU for SIL Testing | Mission Integrator (TBD) | 15-Oct-09 | |
| NPS Operations Plan - Launch Ops/VAFB | Mission Integrator (TBD) | 1-Oct-09 | |

Table 1. NPSCuL Schedule and NROL–41 Deliverables

developed hardware and software models of the sequencer, interfaced with third-party developers, and produced the sequencer requirements document. The author of this thesis is the integration and test manager, and was responsible for the environmental and functional test plans and for coordinating the development of appropriate ground support equipment (GSE) to enable transportation and integration of the payload onto the Centaur.

### 3. Solutions to Support Launch on NROL–41

Any technology development program must simultaneously manage three critical constraints: cost, performance, and schedule. Some of the new structural testing requirements associated with flying P-PODs on the ABC adapter fell to other agencies: Cal Poly agreed to adjust the test requirements for the P-POD system, and ULA included system-level vibration testing (to the full envelope specified for ABC) in the sequencer statement of work (SOW). This left NPS as the developer of the physical structure of NPSCuL-Lite. The requirements for the structure were:

- Meet the physical envelope requirements of the ABC, including mass, volume, and center-of-mass.
- Have dynamic characteristics consistent with the ABC, including a first natural frequency of greater than 35 Hz.
- Support eight fully-loaded P-PODs through the ground handling and launch environments with minimal risk to the CubeSats and the launch vehicle primary payload.
- Ensure that the harnesses are properly routed and appropriately affixed to the NPSCuL-Lite structure for successful deployment of CubeSats.

Given the modest funding available to begin design and testing, the NPSCuL Team members identified trade space between the budget and the fidelity of the structural tests. Since Cal Poly would provide detailed analysis of the P-POD, NPS had to prove only that the fully loaded NPSCuL-Lite structure could survive the launch while attached to ABC without harming any of the

subsystems attached to it. So, investment in high-cost, flight-quality P-PODs was not required. Instead, the NPSCuL-Lite structure could be tested using mass models to simulate the P-PODs.

The structural design of NPSCuL-Lite was developed before the sponsor committed to a single designer for the sequencer; this meant that the sequencer system could only be evaluated in terms of mass during the qualification tests. The NPSCuL program allotted a maximum mass and volume to the sequencer based on conversations with the expected manufacturer. These requirements were made clear in the functional requirements document for the sequencer. Based on the maximum allowable mass and volume, the NPSCuL sequencer engineer produced a mass model of the sequencer unit which would be suitable for the vibration tests. Lack of a stable sequencer design also meant that the wiring harness from the sequencer to the P-PODs, and from the ABC to the sequencer, could not be produced; structural qualification testing therefore did not include any harnesses.

Mass models are commonly used to reduce the cost of spacecraft structural testing. They also shorten development times because the structure can be tested before the subsystems are fully constructed. The qualification testing of NPSAT1, performed in 2007, used many mass models to simulate the subsystems; the NPSCuL Team relied on this in-house knowledge and felt confident that mass models would provide sufficient fidelity for both qualification and acceptance testing.

The qualification test plan for NPSCuL did not include any functional tests, because there were no functional components available when the qualification tests were performed. The decision to perform the qualification tests without any functional hardware was made to satisfy the requirements of the 18-month development schedule within the available budget. Throughout the procurement of the test hardware, NPS sought funds to obtain a high-fidelity P-POD

engineering unit, complete with an operable non-explosive actuator (NEA) which could be activated after completion of the dynamic structural tests. As of the writing of this thesis, these test items remain unavailable.

Concurrent with the production of test equipment, the launch provider began work on ground support equipment for NPSCuL-Lite, requiring coordination with the NPSCuL Team. The team readily accepted these challenges in the absence of an integrating contractor, in spite of limited funding and resources. Relying heavily on the experience of the ULA engineers, the NPSCuL Team made significant strides in ensuring safe handling of NPCuL-Lite at the launch site. This work is described in detail in Chapter IV.

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# II. P-POD MASS MODEL (P2M2) DEVELOPMENT

## A. P-POD MASS MODEL (P2M2) DESIGN AND CONSTRUCTION

### 1. P2M2 Design

The NPSCuL P-POD Mass Models (P2M2s) were designed to serve two functions: to induce realistic stresses on the NPSCuL-Lite structure during vibration testing, and to be used as tools to investigate the integration process. For this reason, the P2M2 design reflected both the maximum mass (with margin) and the external dimensions of actual P-PODs. Design of the P2M2 was based on a unit produced by Cal Poly for their initial development of the P-POD. Very little documentation was available regarding the Cal Poly model, but the NPSCuL Team was given free rein to disassemble the existing mass model in order to reverse-engineer the design. The Cal Poly P2M2 consisted of seven components: a square housing, two end plates, two solid cylinders, and two support brackets. Once disassembled, the parts were measured and weighed, and a CAD model was used to verify the mass properties of the components and the entire assembly. The P2M2 designed for NPSCuL was composed of the same number of parts, though some of the dimensions were altered. The nomenclature of the components, referenced throughout this thesis, are as follows (see Figure 1):

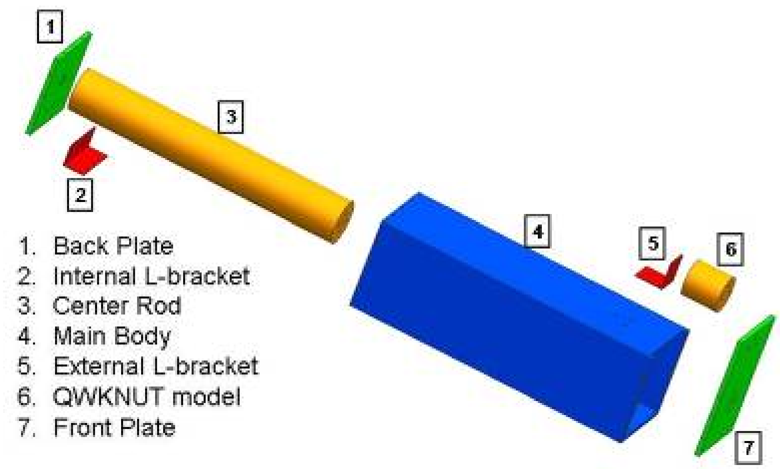


Figure 1. Exploded view of NPSCuL P-POD Mass Model (P2M2) components

The NPSCuL P2M2 design required two refinements to the Cal Poly model. First, counterbores were cut for the screw holes in the Main Body (4) so that the model matched the shape and volume of an actual P-POD. Second, the mass was increased by making the Center Rod (3) larger. The intent of this design change was to account for the fact that CubeSats do not always meet the design specifications in the ICD, especially with regard to mass. Notably, NASA's GeneSat was a 3U CubeSat that weighed about 4.6kg.[8] This precedent made it imperative that the NPSCuL structure be tested with the maximum mass of a P-POD attached. The simplest way to increase the mass while maintaining the center of gravity was to increase the diameter of the Center Rod (3) (since the length was fixed), and then increase the length of the QWKNUT Model (6) to shift the center of gravity back to its intended location. All of these modifications were verified in the CAD model before material was purchased. Table 2 gives the mass properties of the P2M2, compared to the nominal mass properties of a fully integrated flight-ready P-POD. Figure 2 shows the coordinate system for the P2M2, which is identical to the coordinate system used for the P-POD.

8 Center for Robotic Exploration and Space Technologies. "GeneSat1 Technology Demonstration Mission," CREST, http://www.crestnrp.org/genesat1/missionReq.html (accessed 27 April 2009).

| | P-POD MK III ICD | | NPSCuL P2M2 | |
|---|---|---|---|---|
| **Total Mass** | 5.25 | kg | 7.02 | kg |
| **Center of Gravity** | | | | |
| **Xg** | 0 | mm | 0 | mm |
| **Yg** | 6.56 | mm | 7.36 | mm |
| **Zg** | 216.63 | mm | 208.26 | mm |
| **Moments of Inertia** | | | | |
| **Ixx** | 0.3317 | kg.m^2 | 0.4301 | kg.m^2 |
| **Iyy** | 0.3259 | kg.m^2 | 0.4267 | kg.m^2 |
| **Izz** | 0.01689 | kg.m^2 | 0.0221 | kg.m^2 |

Table 2. P2M2 mass properties compared to P-POD MKIII ICD

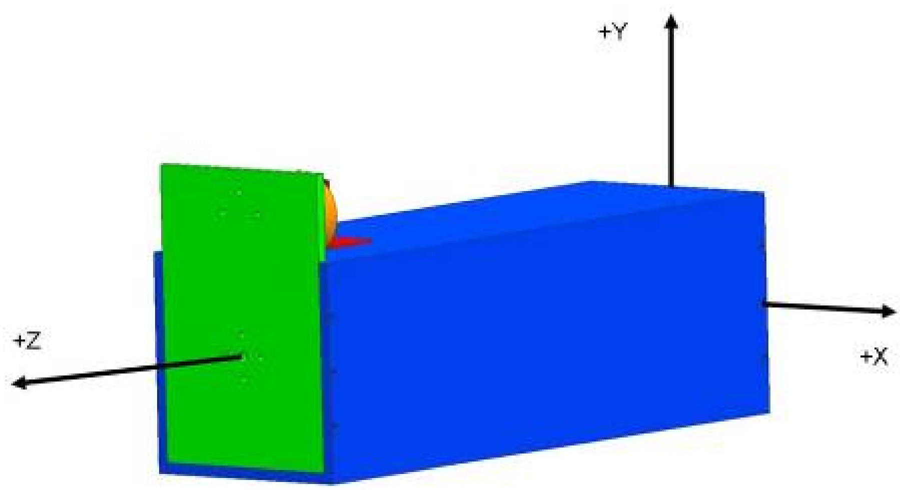


Figure 2. NPSCuL P-POD Mass Model (P2M2) coordinate system

### 2. P2M2 Construction

The NPS SSAG Machine Shop fabricated components for nine P2M2 units using the design supplied by the author and commercially procured materials. Upon delivery of the machined parts, several NPSCuL Team members took part in the assembly. Strict quality control measures were followed, including a standardized construction procedure, a construction checklist that required signatures by the builder and a quality assurance

inspector, traceability of all fasteners by lot number, and traceability of tool calibration data.  Once completed, the builder assigned a serial number to each P2M2, allowing every test, modification, or major event in the life of a P2M2 to be tracked on a “traveler log” document.

While the P2M2 is a non-functional, non-space-rated testing device, the NPSCuL Team treated it, in many ways, as though it were flight hardware.  This was done to familiarize the team members with both the physical handling requirements and the “paper trail” of documentation requirements that could reasonably be expected for the production of spaceflight hardware.

The first P2M2 unit, P2M2-001, underwent its own battery of structural developmental tests to ensure that the P2M2 would be suitable for use in further testing of the NPSCuL-Lite engineering unit.  Sine sweep and random vibration tests in all three axes, up to the ABC qualification level, verified that the models would survive while attached to NPSCuL-Lite during qualification and acceptance testing.  All testing was documented in detail, including data on anomalies during the test and subsequent changes to the design.  Furthermore, the P2M2–001 tests served to familiarize the team with test equipment operation and results analysis months before the actual testing of NPSCuL-Lite.

In summary, the design, construction, and testing of the P2M2 were critical to later testing of NPSCuL-Lite, and this process paid huge dividends in developing the technical and procedural expertise of the team.  The NPSCuL-Lite qualification unit and the sequencer mass model were developed using the physical engineering controls identified during P2M2 production.

## B. P-POD MASS MODEL (P2M2) DEVELOPMENTAL TESTING

### 1. Fundamentals of Vibration Testing

The purpose of dynamics testing of spacecraft is to ensure that the spacecraft design is robust enough to survive the severe dynamic and static

loads encountered during launch.[9] Two separate rounds of testing are normally performed. Qualification testing is used to ensure that the design is robust enough to survive the environment with margin. Qualification testing levels always exceed the maximum predicted environment of the launch vehicle so, when feasible, these tests are performed on a dedicated qualification unit that is never intended to fly.[10] Acceptance testing is performed only on flight hardware; it follows qualification testing and is done to detect flaws in manufacture or construction. Acceptance testing envelopes the maximum predicted environment for the launch vehicle. For payloads flying on legacy launch vehicles, the environments are generally well known, and the launch provider dictates the payload test requirements based on data from previous launches. The structural requirements will normally include a minimum fundamental frequency, expected acoustic vibration environment, expected random vibration environment, and shock loads.

The P2M2 was designed strictly as a tool to reduce costs associated with qualification and acceptance test of NPSCuL and NPSCuL-Lite; it was not designed for use on an actual launch, and there were no formal test requirements for the P2M2 when it was originally procured. The motivation behind running qualification-level tests on the P2M2 was threefold: to test the robustness of the design, to ensure the vibration test equipment was functional, and to educate the student design team. Since the P2M2 was eventually to be installed in flight hardware, it was necessary to verify that the P2M2 would not damage the NPSCuL-Lite structure during its qualification and acceptance tests. Also, NPS had recently acquired a new electrodynamic shaker, which was not yet installed in a permanent facility; if this equipment was to be used to test NPSCuL-Lite, it would have to be temporarily installed and run through a functional check. Most importantly, the student engineers on the project needed

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9 Alan Scott, “An Analysis of Spacecraft Dynamic Testing at the Vehicle Level” (Master’s thesis, Naval Postgraduate School, 1996), 46.

10 United States Air Force, *Test Requirements for Launch, Upper Stage, and Vehicles, MIL-HDBK-340A* (U.S. Department of Defense, 1991), 34.

a base of knowledge and experience with structural test equipment operation and results analysis that could best be realized by running a series of tests on space-related hardware. Characterization of the dynamic response of the P2M2 under test conditions was considered secondary to the goal of learning what to do, and what *not to do*, to qualify a spacecraft structure that will fly on a multi-million dollar launch vehicle. The P2M2 structural tests consisted of only sine and random vibration tests; these tests are briefly described in the next section. Additionally, the sine-burst test is presented because it was employed on the NPSCuL-Lite structure.

#### *a. Low-level Vibration—Sine Sweep Test*

A space payload that is relatively "stiff" has a fundamental frequency, or first normal mode, which is significantly higher than that of the launch vehicle. Launch providers specify a minimum fundamental frequency to prevent dynamic coupling between the payload and the launch vehicle (which could potentially overstress the vehicle-payload system). As long as the fundamental frequency of the payload meets the minimum frequency provided by the launch provider, the payload provider may consider loads experienced in the low-frequency range as quasi-static.[11] United Launch Alliance requested that all modes below 100 Hz be fully represented in the finite element model (FEM) supplied by the secondary payload manufacturer for the launch vehicle coupled loads analysis (CLA). This also meant that if the first fundamental frequency were above 100 Hz, the CLA of the launch vehicle would treat the secondary payload as a lumped mass with no significant frequency content. The fundamental frequency of a payload is determined both analytically, by performing a modal analysis on a finite element model, and practically by means

11 Alan Scott, "An Analysis of Spacecraft Dynamic Testing at the Vehicle Level" (Master's thesis, Naval Postgraduate School, 1996), 46.

of a sine sweep on an electrodynamic shaker. Designers of primary space payloads typically target first-mode frequencies in excess of 35 Hz; secondary payloads are typically designed for fundamental frequencies in excess of 50 Hz.

A sine sweep test is performed using an electrodynamic shaker to vibrate the article under test at a constant acceleration level over a continuous spectrum of frequencies. The output of the test can be measured in terms of displacement, velocity, or acceleration relative to the input of the shaker; typically it is measured by an accelerometer mounted on the article under test. At frequencies outside of a resonance, the article under test will exhibit minimal acceleration relative to the shaker. For example, if the shaker vibrates at 20 Hz at 1 g, the accelerometer on the article under test will also measure 1 g at 20 Hz. When the article under test vibrates at one of its resonant frequencies, the accelerometer will measure a significantly greater or lesser acceleration compared to the shaker. Using the same example, if the shaker vibrates at 200 Hz at 1 g, the measurement accelerometer might register 5 g at 200 Hz, indicating that the article under test is vibrating independently of the input force, and therefore has a resonance at 200 Hz.

The sine sweep is normally conducted to verify the results of an analytical model, such as a FEM modal analysis, and serves as a baseline to detect changes in an assembly that may result from more severe structural testing. The sine sweep test is usually performed at a much lower level than random vibration or shock testing, since the output of interest is characteristic of frequency only.[12]

#### *b. Random Vibration*

The random vibration environment of a launch vehicle is driven by both acoustic vibration and vibrations produced within the launch vehicle itself. The launch provider specifies a Maximum Predicted Envelope (MPE) for random

12 Alan Scott, “An Analysis of Spacecraft Dynamic Testing at the Vehicle Level” (Master’s thesis, Naval Postgraduate School, 1996), 58.

vibration testing; acceptance tests do not exceed MPE, while qualification tests are conducted at much higher levels (MPE +6 dB, or a factor of four). While the MPE includes the low-frequency environment, the payload typically experiences maximum acceleration levels at middle to higher frequencies. This frequency dependence is reflected in the test requirements. Testing is performed in each of the three primary axes of the spacecraft. The purpose of random vibration testing is to ensure that the primary structure, and any electronic or mechanical components can withstand the vibration environment without loss of integrity or functionality.

In a random vibration test, the controller drives the shaker to accelerate the article under test in a random fashion; there is no stepping from frequency to frequency as in a sine sweep. Instead, the shaker input voltage is varied to maintain frequency-dependent levels of acceleration dictated by the user input. Typically, low accelerations are specified at low levels, which ramp up logarithmically to a maximum level at the mid-range frequencies, and then decrease logarithmically across the high levels up to the end of the frequency range. The controller generates a pseudo-random signal that is a composite, or sum, of fixed frequency sine wave signals, and sends this signal to the shaker. So, when the control accelerometer on the shaker measures a certain frequency, the controller drives the shaker to the corresponding acceleration level.

Launch providers specify random vibration requirements in terms of Acceleration Spectral Density (ASD), with units of $g^2$/Hz. This seems odd because the accelerometers measure only acceleration, in terms of g. However, the accelerometers are measuring acceleration over a wide spectrum of frequencies at any one time, and the input/output levels vary with the frequency. The reason for using $g^2$/Hz units is to normalize the measurements of the accelerometers across the spectrum.

### c. *Sine Burst Test: Quasi-static Loads*

Static loads on a structure are frequency-independent loads induced by forces for a limited time. During launch, a spacecraft experiences static loads due to the acceleration of the launch vehicle; the spacecraft can be strength tested against these static loads in a variety of ways, but the sine burst test is often easier and less expensive to execute.[13] The sine burst test applies a quasi-static load to a structure by means of a shaker. The loads are quasi-static because there is some oscillation, but the frequency is well below the fundamental frequency of the structure, so that no dynamic response occurs. In this way, the static loads test requirements can be satisfied using the same equipment used for random vibration and sine sweep tests.

The launch provider determines acceleration load factors in units of g, including the vertical and lateral components of the acceleration. Since the sine burst test is performed in the principal axes of the spacecraft, the test load factor must be the root-sum-square of the launch vehicle load factors. A factor of safety (FS) can then be applied; industry standard for qualification testing is FS = 1.25.

## 2. P2M2 Vibration Test Objectives

The launch provider typically determines the level of testing required for spacecraft structures and promulgates these requirements in the payload/LV Interface Control Document (ICD), which is developed after the official launch manifest is approved. For the sake of secondary payload developers whose test requirements are all similar, launch providers often publish a "User's Guide." The User's Guide is a means of publishing flight requirements (including testing

13 National Aeronautics and Space Administration, "NASA Preferred Reliability Practices; Sine Burst Loads Test (PRACTICE NO. PT-TE–1420)." Goddard Space Flight Center, Greenbelt, MD. http://klabs.org/DEI/References/design_guidelines/test_series/1420.pdf (accessed 13 May 2009).

requirements) to satellite developers who may or may not be manifested on a launch. This document provides a baseline for development and testing in lieu of a formal ICD.

ADaMSat, the first mission for NPSCuL-Lite, will be hosted by the first flight of the Aft Bulkhead Carrier. While the launch vehicle, the Centaur upper stage of an Atlas rocket, has a long history of success, the ABC is completely new. The launch provider, United Launch Alliance (ULA), drew upon historical telemetry data to characterize the launch environments in the vicinity of the ABC; but this data was collected when a helium bottle was mounted in that vicinity. Therefore, there is some uncertainty about whether the launch environments experienced on previous flights are sufficiently similar to those felt by a secondary payload riding on the ABC. A draft User's Guide was presented in December 2008, which provided the results of some of ULA's preliminary analyses. This draft User's guide served as the basis for planning the tests of the P2M2.[14]

While the User's Guide gave a detailed acoustic environment schedule, the ABC structural designer, at the ABC kickoff meeting in December 2009, stated that separate acoustic testing would not be necessary for secondary payloads on the ABC because the random vibration test spectrum enveloped the expected acoustic environment. Additionally, the shock environment was still under investigation, so no shock testing requirements were available. This left static loads, low-frequency vibration, and broad-spectrum random vibration as the minimum SP test requirements. Static loads testing of the P2M2 was inappropriate because the P2M2 was not intended for flight so only low-frequency vibration and random vibration were considered applicable to the P2M2. For low-frequency vibration, the NPSCuL Program Team chose a target first mode frequency of 50 Hz as the lower limit design goal. The random vibration test spectrum would have to match the spectrum in the User's Guide. It

14 United Launch Alliance, Aft Bulkhead Carrier Secondary Payload User's Guide (draft), ULA-ATLAS-UG-08-001, Denver, 2008.

is important to note that all P-PODs produced to-date were tested to the NASA General Environmental Verification Specification (GEVS) standard.[15] When the ABC environments were published, they were found to be at higher levels and therefore trumped the GEVS requirement. The P-POD provider, Cal Poly, agreed that Cal Poly would perform additional testing on the P-PODs to ensure it could withstand the harsher environment.

Tables 3 through 5 and Figure 3 show the environmental test parameters for NPSCuL-Lite as dictated by the launch provider. The P2M2 was subjected only to sine sweep and random vibration; all three sets of parameters were applied to the NPSCuL-Lite qualification unit, as described in Chapter III.

| Test Parameter | Parameter Value |
|---|---|
| Frequency Range | 15 Hz - 2000 Hz |
| Acceleration | 0.25 g (max.) |
| Sweep Rate | 2 Octaves/min. |
| No. of sweeps | 1 up + 1 down = 2 total |
| Measurements | 1 per sweep (frequency spectrum) for each channel (control and measurement) |
| Processed data | 1 FRF for each measurement channel per sweep |

Table 3. Sine Sweep Test Parameters for ABC

| **ABC Secondary Payload Limit Loads** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Limit Load (g)** | | | **Root Sum Square** | **Factor of Safety** | **Test Load (g)** | | |
| X | Y | Z | | | X (FSx) | Y (FSy) | Z (FSz) |
| 5.0 | 5.0 | 7.0 | 9.9 | 1.25 | 12.44 | 12.44 | 12.44 |

Table 4. Sine Burst Test Parameters for ABC

15 Wenschel Lan, "Poly Picosatellite Orbital Deployer Mark III ICD." California Polytechnic State University, San Luis Obispo, 2007.

| Frequency (Hz) | MPE ASD (G^2/Hz) | Qualification ASD (G^2/Hz) |
|---|---|---|
| | | |
| 20 | 0.03 | 0.12 |
| 40 | 0.125 | 0.5 |
| 240 | 0.125 | 0.5 |
| 2000 | 0.003 | 0.012 |
| overall | 7.6G(RMS) | 15.2G(RMS) |
| duration | 60 sec/axis | 180 sec/axis |

Table 5. Centaur ABC requirements for secondary payload (SP) random vibration test based on maximum predicted environment (MPE) and typical qualification levels (MPE +6dB)

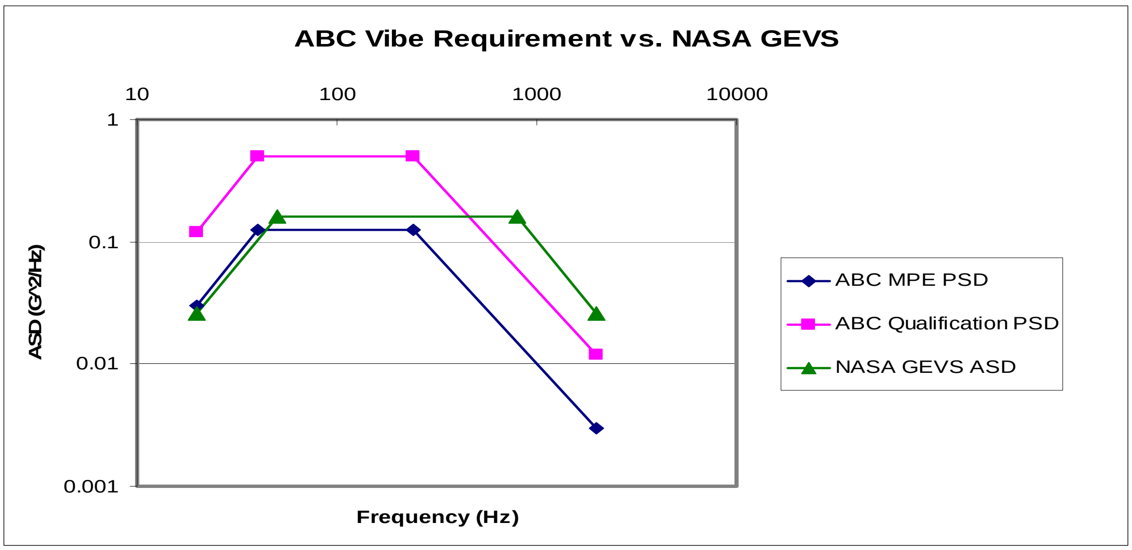


Figure 3. Comparison of NASA GEVS vs. ABC Vibration Test Requirements

### 3. Operation of the NPS Vibration Test Facility

The necessary vibration test equipment was installed temporarily in a laboratory to support NPSCuL-Lite Qualification testing. This facility was first used for the qualification of the P2M2 design. It consisted of a PC workstation running the M+P Vibrunner software suite, a Ling 612VH electrodynamic shaker

(with its amplifier), a slip table, a data acquisition system, a power conditioner, and various piezoelectric accelerometers. The basic signal flow for a closed loop vibration test is shown in Figure 4.

Closed loop vibration was used for both sine sweep tests and random vibration. In a closed loop scheme, the software outputs a digital signal to represent its estimate of the voltage required to produce the desired level of force from the shaker. The data acquisition system (DAQ) converts this to an analog voltage, which is then amplified and sent to the electromagnet in the shaker. The shaker armature moves in response to the force of the electromagnet, and a control accelerometer mounted at the interface between the shaker and the article-under-test, or as close to this interface as possible, measures the input acceleration. This signal is routed back through a power conditioner and through an analog-to-digital converter in the data acquisition system to the PC, which analyzes the result and adjusts its output to maintain the desired vibration forces. Measurement accelerometers are also located at points of interest to measure the dynamic response.

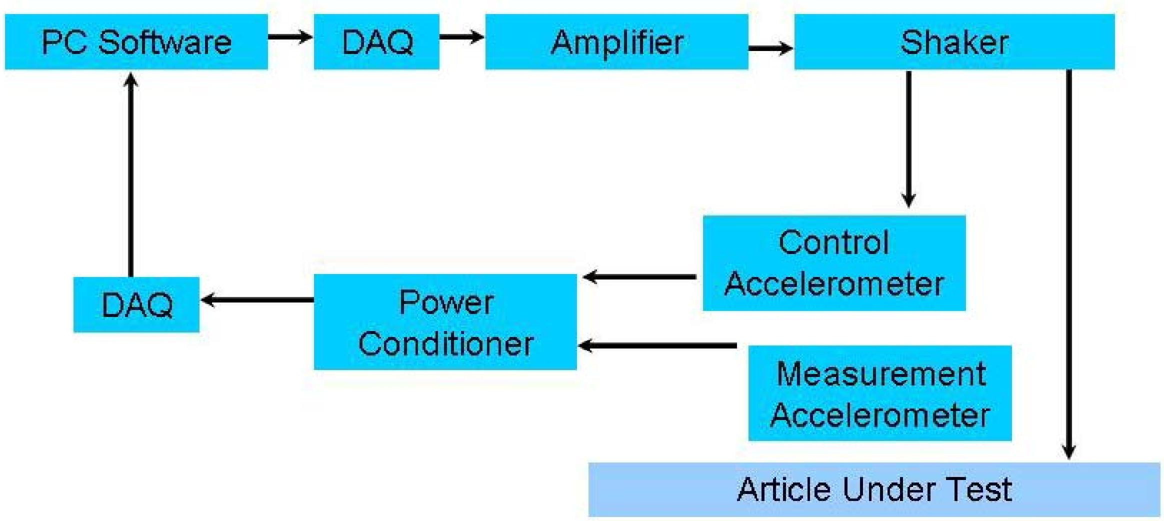


Figure 4. Signal flow for closed-loop vibration test control

The Ling 612VH is capable of generating up to 6000 lbs of force (peak) in sine vibration, 6000 lbs RMS (root mean square) of force in random vibration, or 18,000 lbs of force (peak) in a quasi-static shock test. It has air bearings that isolate it from the floor and are adjustable depending on the weight of the article attached to the shaker. It also has a 7.5 HP external blower to cool the armature during operation. The shaker produces vibrations in only one direction; a slip table can be attached to the shaker to produce vibrations in the horizontal direction. The slip table is a magnesium plate maintained on a thin film of oil that is fed by a hydraulic pump, providing a virtually frictionless environment.

The M+P Vibrunner software controlled each test. Necessary input parameters included the specifications of the shaker, the mass of the article under test and the test fixtures, the random vibration spectrum provided by the launch provider, and calibration data for each of the accelerometers. Additionally, the user dictated the times during each vibration test when the software automatically took measurements from the accelerometers. The digital to analog converter, supplied by VXI Technologies (now VTI Instruments) had a 16-channel I/O interface for up to 16 single-axis accelerometers. The only suitable power conditioner available for testing was a 12-channel unit with one faulty channel; so only 11 channels were actually available.

One item of critical importance in vibration testing is the design of the vibration fixtures. Because the article under test usually cannot be affixed directly to the shaker or the slip table, fixtures must be designed to mate the article under test to the shaker or slip table. Two considerations drive the design of the fixture: it should have the minimum necessary mass so that it does not increase the test mass beyond the maximum capability of the shaker, and it must be sufficiently rigid so as to not couple with the shaker while under dynamic loads. Provided that the first natural frequency of the fixture is greater than that of the shaker, coupling will be avoided and the force input from the shaker armature will transfer directly to the article under test.

The slip table for the Ling 612VH was not available for use during P2M2 testing. Since the shaker vibrates in only one direction, two fixtures were designed to attach the P2M2 to the shaker to allow testing in three axes.[16] Both fixtures shared a common method of attaching to the shaker, via a 1” thick, 16” square aluminum (AL-6061) base plate weighing about 11 kg. The Y-axis fixture consisted of a single, 0.5” thick, 4.5 kg aluminum plate that would mount to the P2M2 first, and then mate with the base plate. The X/Z-axis fixture consisted of a 0.5” thick upright, mated directly to the base plate, and two triangular buttresses that engaged the upright and the base plate, and weighed about 6.5 kg. These fixtures are depicted in Figures 7, 10 and 14.

The fixtures for the P2M2 qualification testing were designed without a full understanding of how vibration testing works. While it was understood that the fixtures needed to be relatively stiff, no modal analysis of the fixtures was performed prior to their construction. Once the fixtures were built, they were tested to capture some of their modal characteristics, but the results were not fully understood until after the P2M2 testing was complete. The post-testing analysis suggested that the fixtures, rather than transferring energy with no additional input, may have acted as additional springs in the spring-mass system between the shaker and the P2M2, and excited modes that may not represent the P2M2’s actual modal characteristics. Although any test fixture will act as additional springs, an improved design of the fixtures would likely have had more mass, but would have been much stiffer than the fixtures used for the tests described below.

### 4. Results of P2M2 Developmental Testing

The first complete run of the P2M2 through the ABC-specified vibration envelope was performed in the Y-axis configuration. No data was received from the measurement accelerometer during the test (due to a bad connection at the

16 The coordinate system of the P2M2 was identical to that of a P-POD, with the Z-axis along the long axis of the unit and the QWKNUT Model (6) situated along the positive Y-axis.

power conditioner), but the control accelerometer accurately recorded that the full input spectrum was attained. The P2M2 was found damaged following the test. The Center Rod (3), which attached to the Front Plate (7) by a single ¼” screw, had deflected under dynamic stress enough to overcome the force of friction, causing the screw to move. Upon inspection, it was clear that the screw was no longer holding the Center Rod (3) in place. The clearance hole in the plate was deformed and the lock washer had dug itself into the aluminum. The test was deemed a failure and the P2M2 was modified to include four #6 screws connecting the Front Plate (7) to the Center Rod (3). Since the fasteners for the center rod are symmetric around the Y- and X- axes, it was decided to move on to the X-axis shake once the modifications were complete.

The next test was performed on the fixture used to shake the P2M2 in the X- and Z- directions, without the P2M2 installed. This would indicate whether the fixture might influence the test. Because the fixture is relatively tall, two separate tests were performed: one with the measurement taken in the same direction as the shaker motion, and one with the measurement accelerometer mounted to measure any transverse (sideways) deflection of the fixture. Figures 5 and 6 show the results.

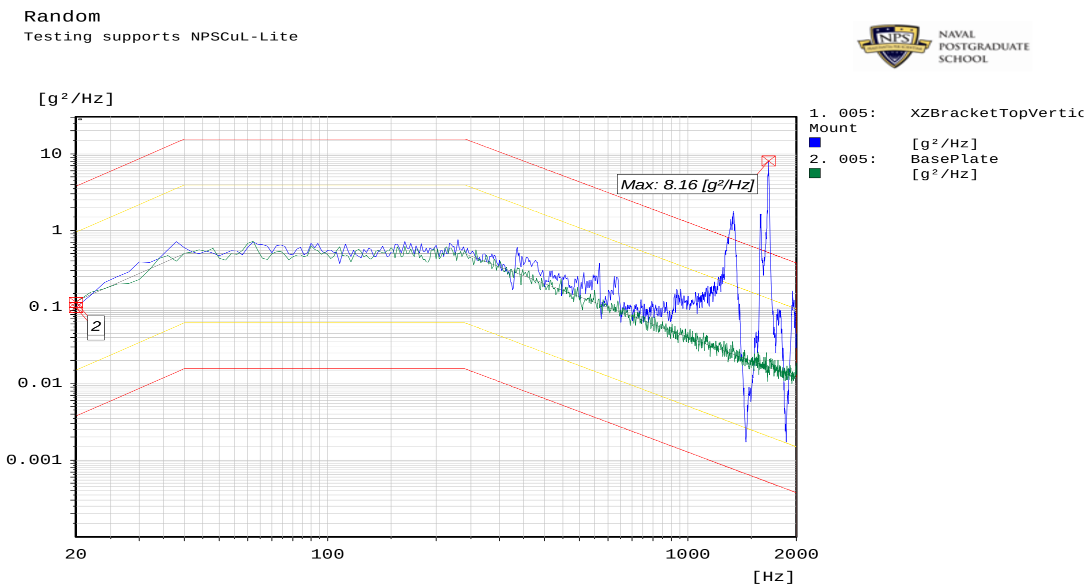


Figure 5. Random vibration, X/Z fixture, control (green), measurement (blue) in the direction of shaker motion

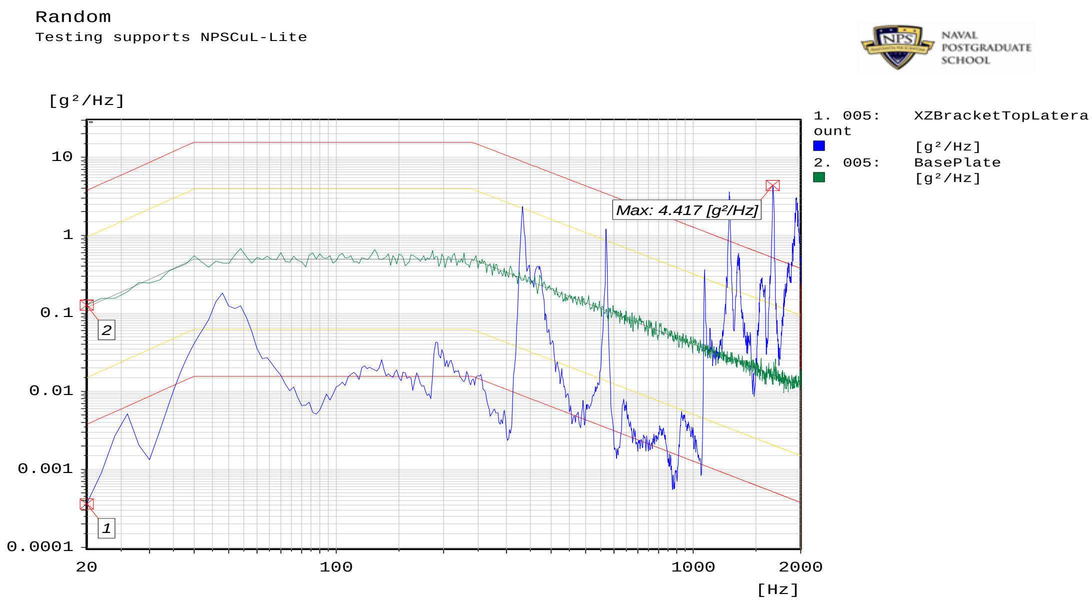


Figure 6. Random vibration, X/Z fixture, control (green), measurement (blue) across the direction of shaker motion

Note that the signal from the control accelerometer was a close match to the test parameters, but the signal from the measurement accelerometer, mounted in the direction of acceleration on the fixture, was not. In an ideal

fixture, these measurements would be closely matched to the control input. Instead, the fixture began to deviate from the shaker input around 320 Hz and showed significant deviations above 900 Hz, which is lower than the natural frequency of the shaker (2.4 kHz). The second test, with the accelerometer measuring lateral deflection of the fixture, indicated accelerations well below the test input until 300 Hz, with several peaks between 300 Hz and 2000 Hz. The upright section of the fixture itself did not couple with the base of the fixture, but it exhibited modes independent of the base of the fixture above 300 Hz in both the vertical and transverse directions. On an ideal fixture, an accelerometer mounted orthogonally to the test axis would measure only a fraction of the test input throughout the spectrum.

The P2M2, mounted to this fixture as shown in Figure 7, survived random vibration test in the X-axis with no significant damage. The first time it was tested, several of the screws connecting the Back Plate (1) to the Center Rod (3) backed out, resulting in the Center Rod (3) becoming free to move and shearing the head of one of the screws. This necessitated a second change to the design to install larger screws and apply staking compound to all screw heads to keep the screws from loosening or backing out. The P2M2 was re-tested after incorporating these changes, and none of the screws failed or backed out. Results of the sine and random vibration tests are shown in Figures 8 and 9.

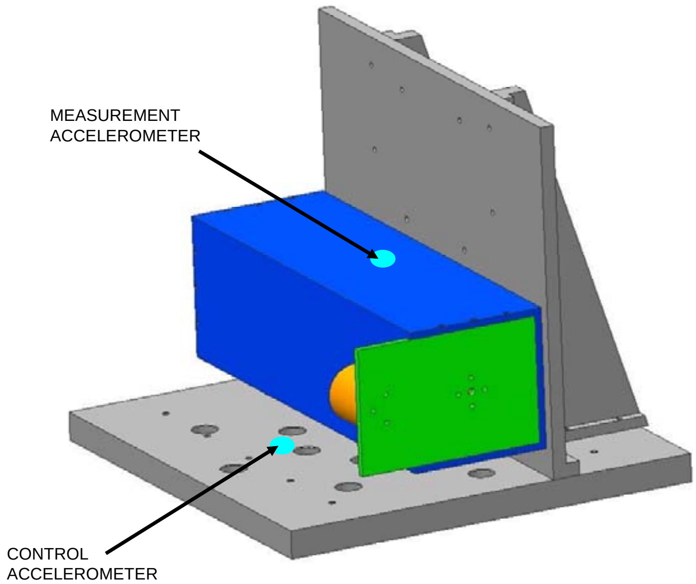


Figure 7. Accelerometer placement for P2M2 sine and random vibration, X-axis

In the sine sweep (Figure 8), the P2M2 exhibited its first mode around 250 Hz, while the random vibration test showed significant attenuation between 200 and 300 Hz. Maximum acceleration measured in the random vibration test (Figure 9) was 24.78 g. It must be noted that because the fixture was not ideal, the peaks and valleys in the graphs represent the natural frequencies of the fixture/P2M2 system and may not represent any independent vibration of the P2M2. Also, at frequencies above 800 Hz (where the fixture showed significant deviation from the control input), the fixture/P2M2 system saw a dramatic increase in accelerations, implying that the fixture coupled with the P2M2 and magnified the shaker input. Finally, the control channel saw a spike at around 1.3 kHz, which did not occur when the fixture was shaken by itself. This indicates that, at higher frequencies, the fixture/P2M2 system excited the base plate of the fixture to the point that the shaker could not maintain the test within the desired parameters. This was seen as either a limitation of the test fixture, or a limitation of the shaker itself. Further discussion of this anomaly is provided in Chapter III.

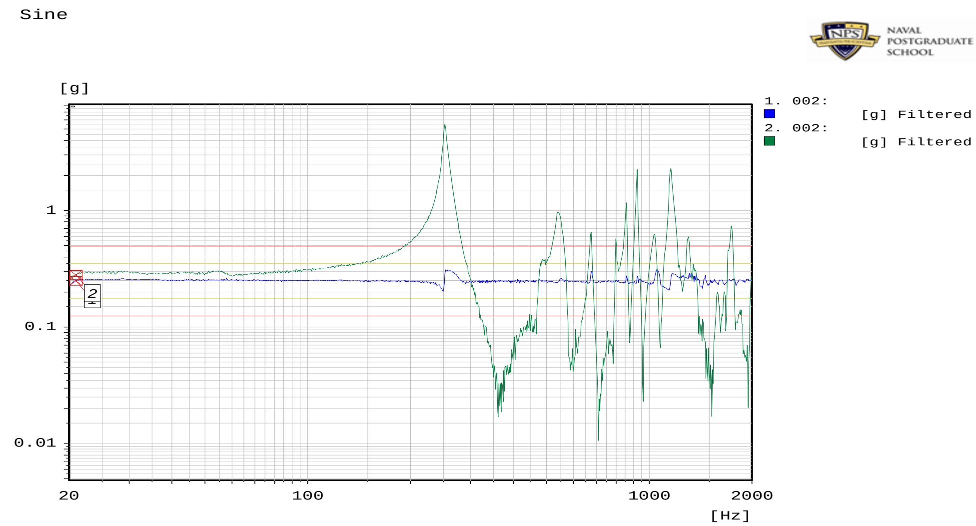


Figure 8. Sine sweep, P2M2, vibration along P2M2 X-axis, control (blue) mounted at base of fixture, measurement (green) near P2M2 CG

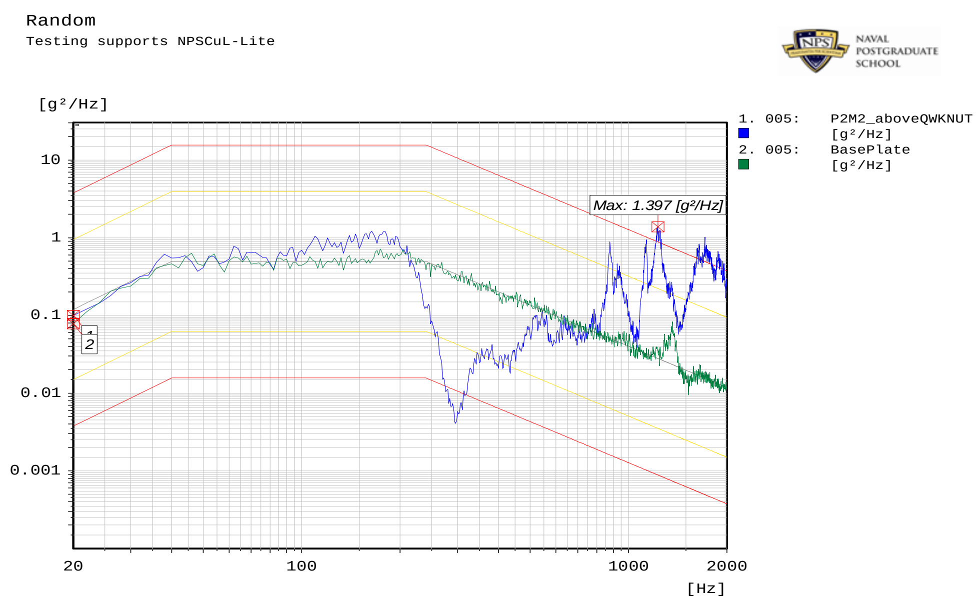


Figure 9. Random vibration, P2M2, vibration along P2M2 X-axis, control (green), measurement (blue), near P2M2 CG

The Z-axis test re-used the X-axis fixture, configured as shown in Figure 10. The fixture was not re-tested by itself. Sine sweep and random vibration tests were completed according to the schedule. After the test, two of the screws connecting the Front Plate (7) to the Center Rod (3) were found backed out of their holes. This resulted in a third modification to the design, using safety wire to prevent the Front Plate (7)—Center Rod (3) screws from backing out. The Z-axis test was not repeated since there was no damage and none of the screws actually came free of the structure. Figures 11 and 12 show the results of testing in the Z-axis direction.

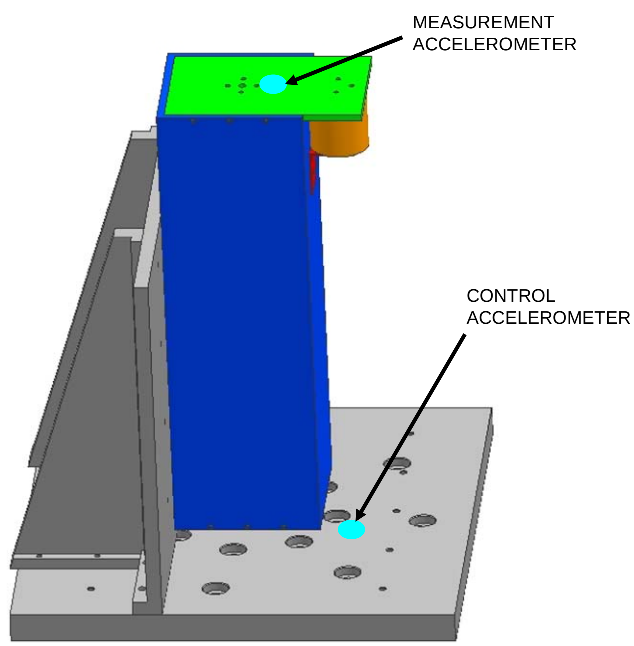


Figure 10. Accelerometer placement for P2M2 sine and random vibration, Z-axis

In the sine sweep of the P2M2 in the Z-configuration (Figure 11), the P2M2/fixture showed a first mode at around 180 Hz, with a second peak at around 450 Hz. The random vibration (Figure 12) showed a first mode at about 200Hz and a second peak at 400 Hz. Again, the control accelerometer had a spike at around 1.3 kHz, as in the X-axis test. This spike is independent of the

orientation of the P2M2 on the fixture, again raising the question of why the shaker was unable to maintain random vibration within the desired test levels. The Z-axis test also had the maximum RM value (45.02 g) for the measured accelerations in any axis. Because the degree of interaction between the shaker, the fixture, and the P2M2 cannot be characterized, the maximum acceleration a P2M2 would experience if attached to an ideal fixture remains unknown. Since the P2M2 survived the test with no damage, the team decided to perform one more test of the P2M2 in the Y-axis as a final go/no-go of the design.

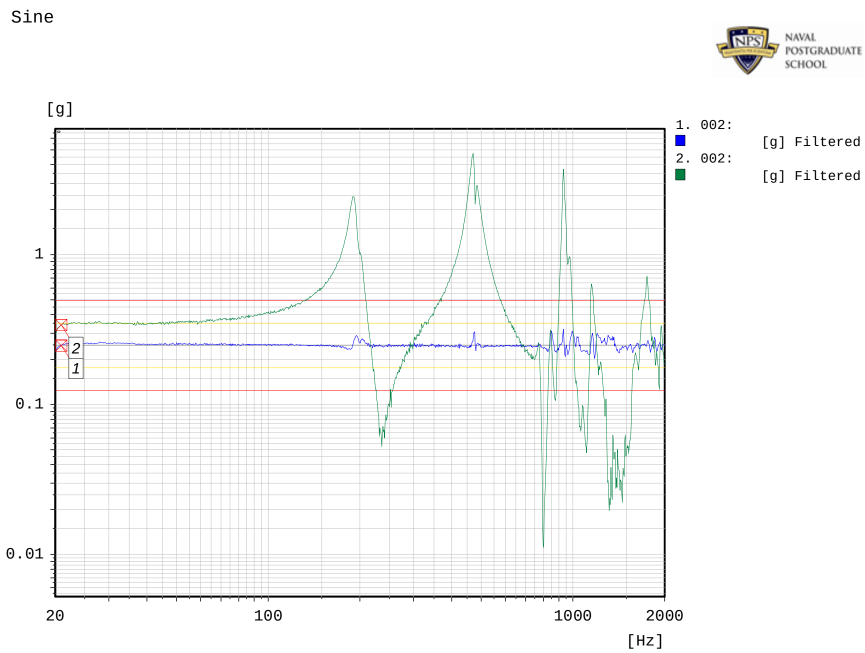


Figure 11. Sine sweep, P2M2, vibration along P2M2 Z-axis, control (blue), measurement (green), near P2M2 CG

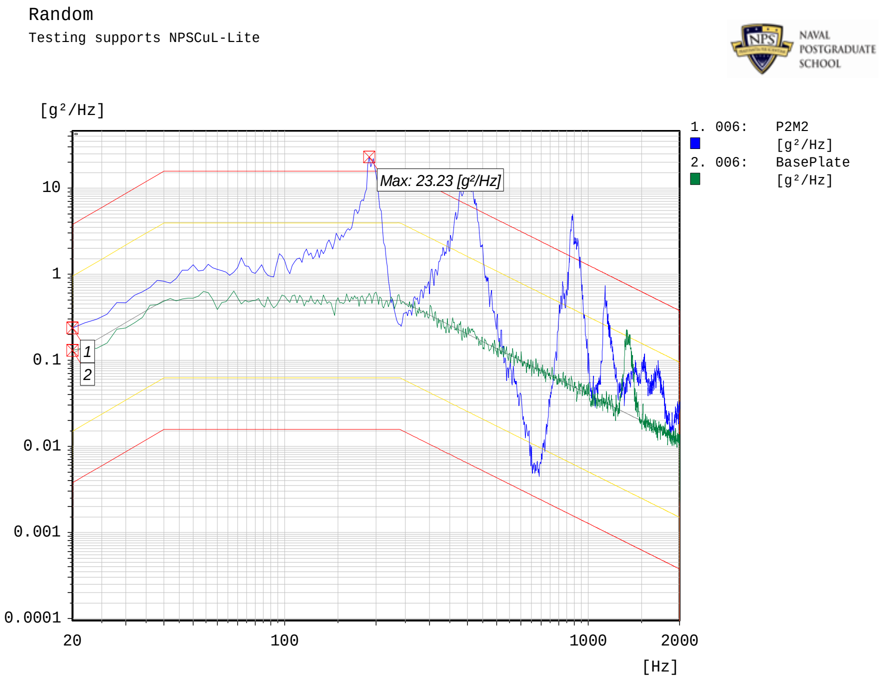


Figure 12. Random vibration, P2M2, vibration along P2M2 Z-axis, control (green), measurement (blue), near P2M2 CG

After reconfiguring the shaker with only the Y-axis fixture, a sine sweep and random vibration were performed, also to characterize how the fixture reacted independently of the P2M2. Results of the random vibration of the Y-axis fixture are shown in Figure 12. When the P2M2 was attached to the fixture (see Figure 14) another series of sine sweep and random vibration tests resulted in no noticeable damage to the P2M2, and the team gave the “go” to the final design of the P2M2. At this time, eight additional P2M2s had been completely manufactured, though without any of the engineering changes that came out of the testing. These eight units were then modified to match the design of the P2M2 as it stood after the Y-axis test. Results of the final Y-axis test of the P2M2 are given in Figures 15 and 16.

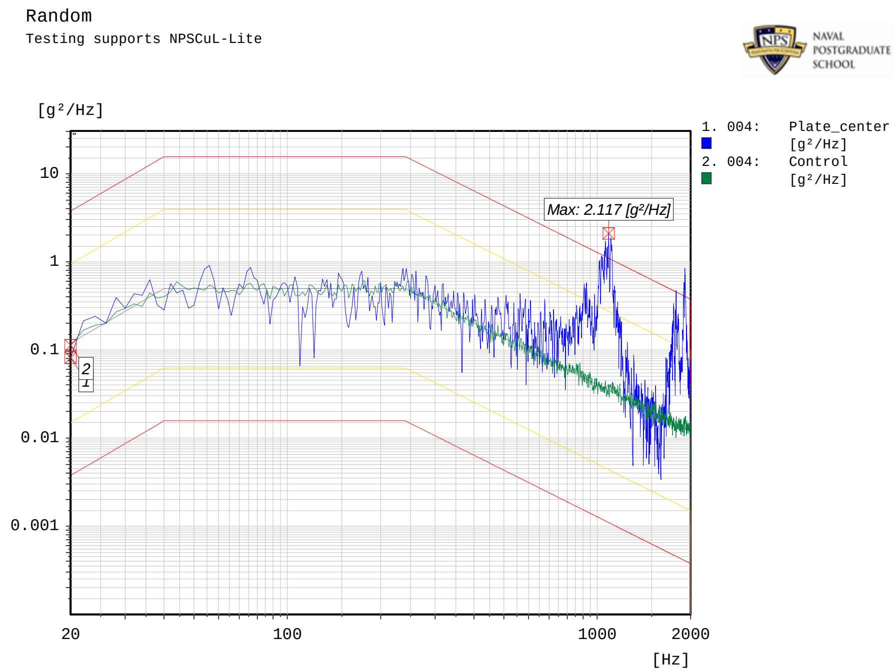


Figure 13. Random vibration, Y-fixture, control (green), measurement (blue), in the direction of shaker motion

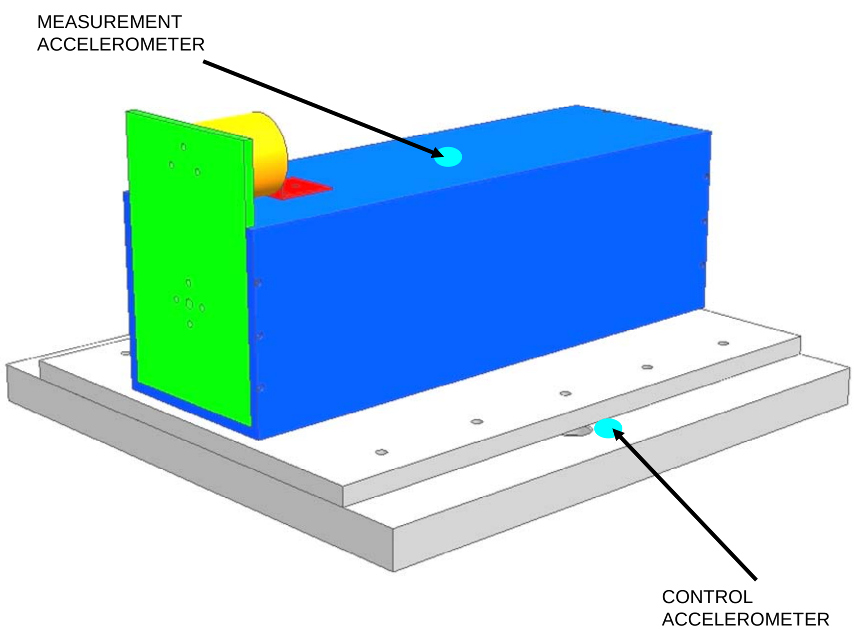


Figure 14. Accelerometer placement for P2M2 sine and random vibration, Y-axis

In the Y-fixture random vibration test results (Figure 13), the control accelerometer matched the desired input, while the measurement accelerometer saw a spike, at around 1.1 kHz, implying that the first mode of the Y-axis fixture was less than that of the shaker base plate. The sine sweep (Figure 15) showed the first mode for the P2M2/fixture at around 490 Hz. When the random test (Figure 16) was performed with the P2M2 involved, the control accelerometer saw a spike at roughly 1600 Hz, again suggesting that the fixture/P2M2 system were coupling in a way that affected the ability of the shaker to control the test. The measurement showed a peak at around 280 Hz with several larger peaks at higher frequencies, and a maximum acceleration of 34.86 g RMS. Though the Y-axis fixture coupled with the P2M2 at higher frequencies than the X/Z axis fixture, the coupling nonetheless occurred within the vibration envelope required for the test.

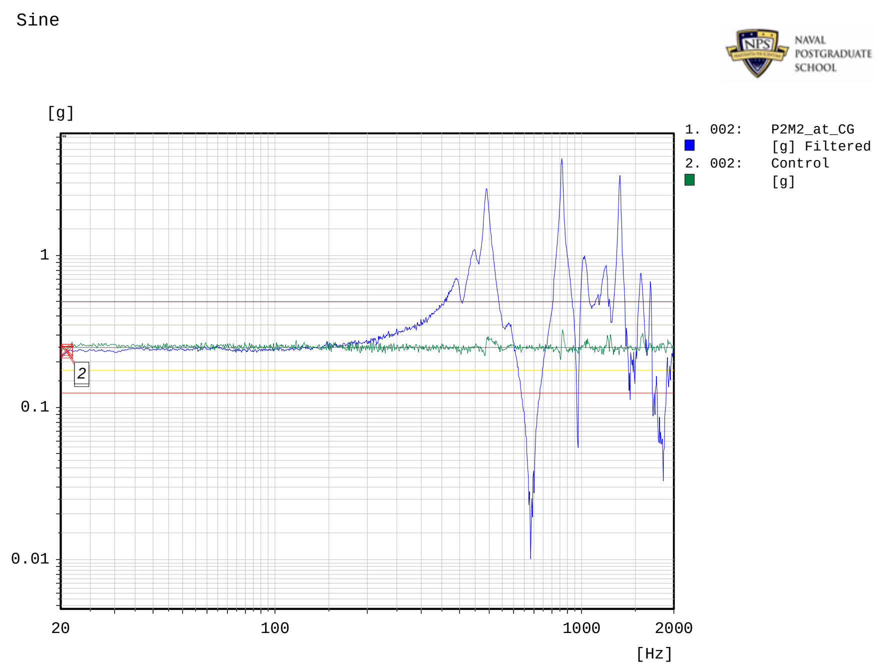


Figure 15. Sine sweep, P2M2, vibration along P2M2 Y-axis, control (green), measurement (blue), near P2M2 CG

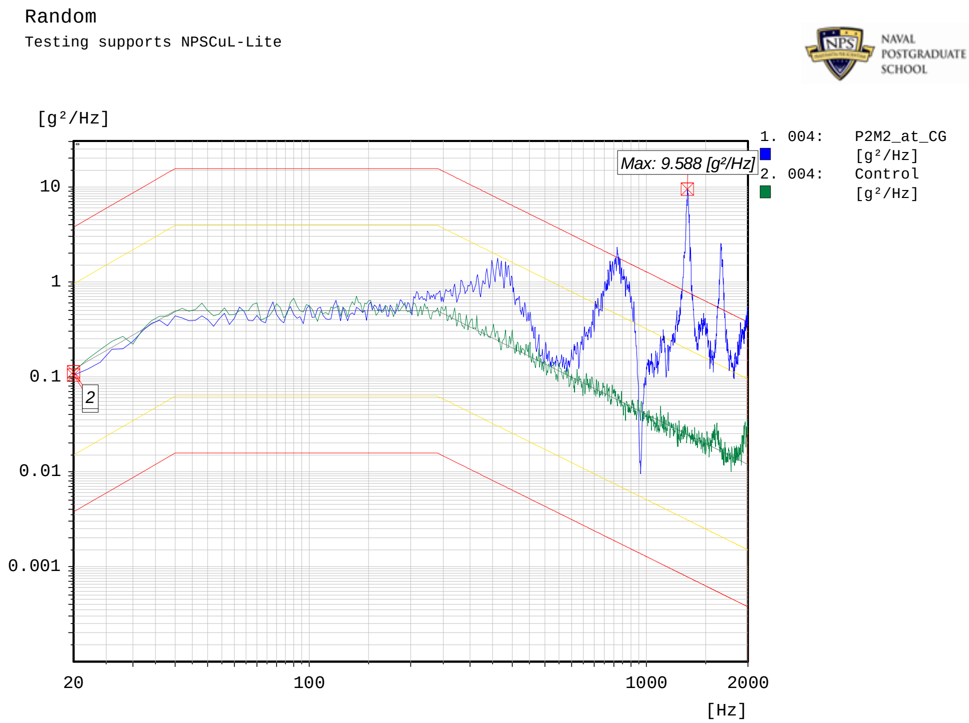


Figure 16. Random vibration, P2M2, vibration along P2M2 Y-axis, control (green), measurement (blue), near P2M2 CG

### 5. Conclusions drawn from P2M2 Developmental Testing

The developmental tests of the P2M2 achieved all the desired goals: the NPS vibration test equipment was shown to be fully functional, the P2M2 was shown to be robust enough for use in NPSCuL-Lite structural tests, and the NPSCuL team gained a wealth of knowledge about how to run the vibration test equipment and properly analyze the results. Additionally, the team learned valuable lessons about the design of the vibration test fixtures that informed the NPSCuL-Lite Qualification Test Plan.

The failure to characterize the response of the P2M2 to the environmental parameters promulgated in the ABC user's guide was not critical to the project, because the response of NPSCuL-Lite to the same environment was still unknown, as was the internal environment of the NPSCuL-Lite structure.

Nevertheless, the NPSCuL team understood that the data collected from the qualification test of the first NPSCuL-Lite structure would be of keen interest to the launch provider, the P-POD manufacturer, and the developers of the CubeSat payloads scheduled to fly on NROL–41. For these reasons, several additions were made to the NPSCuL-Lite test plan. First, the plan would require a thorough analysis of the intended test fixture to ensure that its fundamental frequency is outside of the range of the test. Second, the test schedule had to be adjusted to allow for practical testing of the fixture independently of the NPSCuL-Lite Qualification article. Third, the test plan should include testing of the fixture while NPSCuL-Lite is attached to the fixture, to ensure that the fixture is behaving properly regardless of whether NPSCuL-Lite is attached to it. Finally, the P2M2 testing suggested that NPSCuL-Lite Qualification testing should include at least 2 accelerometer channels devoted to characterizing the internal environments of the structure. This data may then be provided to the P-POD manufacturer to inform the acceptance testing of the P-PODs to be provided for the launch.

### 6. Future P2M2 use as Flight-qualified Mass Models

It is conceivable that CubeSats and/or P-PODs might not be fully developed and integrated in time for delivery to the launch site. In this situation, a mass model of the intended flight P-POD would be required to allow NPSCuL-Lite to launch with minimal impact to the mission. The P2M2 described in this thesis was intended for use in structural testing only; to be flown on an actual launch, a mission-unique P2M2 would be required.

Recall the initial requirements of the P2M2: structural characterization and volume simulation. Neither of these requirements would apply to a flight-quality mass model, as both would be previously satisfied. Instead, a flight-quality mass model need only simulate (accurately) the mass of the previously intended component, and be as safe for flight, or safer, than the intended component. Better quality engineering and simplification of design would achieve both these goals: considerations for future work are as follows:

1. Simplify the design by removing the QWKNUT model (6) and bracket (5). These were included in the test-quality P2M2 to provide accurate CG and modal characteristics for testing. A flight-quality P2M2 only needs to simulate a mass, so it would be acceptable to simplify the design as much as possible. This could possibly be milled out of a single block of high-quality aluminum, which would also ensure a frequency high enough to have no significant frequency-dependent reactions to input forces. This would not be sufficient, however, if the launch provider requires that the mass model demonstrate the frequency-dependent characteristics of an actual P-POD. In this case, a multi-component P2M2 would be more suitable.

2. Adjust the mass of the P2M2 by adjusting the center rod (3). This could be done by ordering a different diameter of solid aluminum rod, or by turning the rod on a lathe to reduce the mass in smaller increments. Total mass of the P2M2 would have to match that of the manifested P-POD, within some tolerance based agreed upon by the integration office and the launch vehicle provider.

3. Install locking screw thread inserts to improve performance. The test-quality P2M2 used a combination of thread-lock compound, staking, and safety wire to prevent damage to screws under severe vibration. These applications were not intended for, or tested under, severe thermal/vacuum environments. Locking screw thread inserts would provide better performance in severe vibration environments without the potential for outgassing or decomposition due to exposure to the terrestrial environment. Any staking compound used must meet MIL-STD, NASA, or similar requirements for flight structures.

4. Flight-quality P2M2s should have similar external surface qualities as a P-POD. The P-POD is prepared with an anodized coating to prevent damage caused by friction with the launch vehicle (in this case, the NPSCuL-Lite

structure).[17] A P2M2 designed for flight must have similar characteristics so that it does not vary significantly from the other P-PODs installed. Additionally, the engagement face of the structure should be ground to a flatness standard compatible with an actual P-POD (again, to reduce wear on the structure of NPSCuL-Lite). There may also be electrical interface requirements, depending on the design of the harness and sequencer.

5. An additional round of testing should be performed, as proto-flight testing, in preparation for the acceptance test of the NPSCuL-Lite structure. Proto-flight testing involves testing a structure to levels equal to, or in excess of, the maximum predicted environment while maintaining the structure's flightworthiness. Since a flight P2M2 will be very different from a test P2M2, it would be prudent to test it as part of the NPSCuL-Lite acceptance testing to ensure its structure will not fail during launch.

17 Wenschel Lan, "Poly Picosatellite Orbital Deployer Mark III ICD," California Polytechnic State University, San Luis Obispo, 2007, 6.

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# III. NPSCUL-LITE QUALIFICATION TESTING

## A. NPSCUL-LITE QUALIFICATION TEST PLAN

### 1. NPSCUL-Lite Test Requirements

Test requirements for NPSCuL-Lite are spelled out in the Engineering Development Unit (EDU) Qualification Test Plan (Appendix A). Only sine sweep, sine burst, and random vibration tests were required. The acoustic vibration environment was enveloped by the random vibration environment; therefore, the launch provider considered qualification testing to the random vibration MPE +6 dB as sufficient to cover the acoustic vibration levels.[18] As of May 2009, the shock environment at the ABC was not finalized and data was not available; therefore the NPSCuL-Lite EDU test schedule did not include shock testing.

The sine sweep, sine burst, and random vibration levels required for qualification testing were previously outlined in Section II.B.2.

## B. STRUCTURAL VIBRATION FIXTURE DEVELOPMENT

The production run of eight additional P2M2s was completed in late April 2009. The first NPSCuL-Lite structure (the qualification unit) was completed at about the same time, and the team quickly rallied to prepare these devices for the structural tests, which took place in May. A slip table compatible with the Ling 612VH electrodynamic shaker became available, so the intent was to use the same fixture for vibration test in all three principal axes.

As mentioned earlier, the P2M2 test results called for a more thorough analysis of the vibration test fixture prior to testing NPSCuL-Lite, to ensure that the modal characteristics of the fixture did not influence the tests. To this end, a three-dimensional finite element model of the fixture was produced and analyzed

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18 United Launch Alliance, “Aft Bulkhead Carrier Secondary Payload User’s Guide (draft),” ULA-ATLAS-UG-08-001, Denver, 2008.

using the ANSYS 11 suite of engineering simulation software. The target frequency for the first mode of this fixture was 3 kHz. After several iterations using the modal analysis function in ANSYS, the design was finalized, with a mass of about 19 Kg. It consisted of a round plate, 17” in diameter, with a 4” diameter cutout in the center to reduce its mass, and a 0.25” channel across the plate to allow accelerometer wires to run directly to the head of the shaker or to the inside of NPSCuL-Lite. The fixture included 16 counterbored holes for attachment to the shaker or slip table and 24 0.25” holes to attach NPSCuL-Lite to the fixture in a manner similar to how it will attach to the ABC. For the FEM analysis, boundary conditions were applied in the regions around the 16 bolt holes at the shaker interface, fixed in both translation and rotation. The results of the finite element analysis of this fixture are shown in Table 6, with the first and third fundamental frequencies displayed graphically in Figures 17 and 18. In all modal analysis graphics in this thesis, the deflections are exaggerated to make them easier to see.

| Mode | Frequency [Hz] |
|---|---|
| 1. | 3276 |
| 2. | 3282 |
| 3. | 3457 |
| 4. | 3459 |
| 5. | 3480 |
| 6. | 4191 |

Table 6. Results of analytical modal analysis of the NPSCuL-Lite structural test fixture using ANSYS engineering simulation software

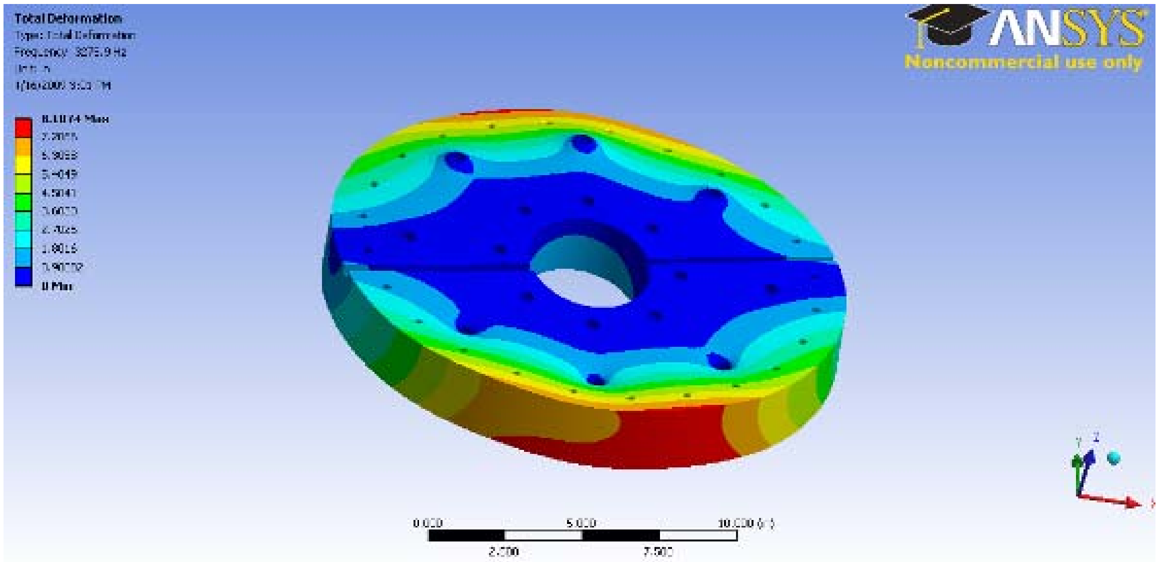


Figure 17. NPSCuL-Lite structural test fixture, first mode ~3280Hz

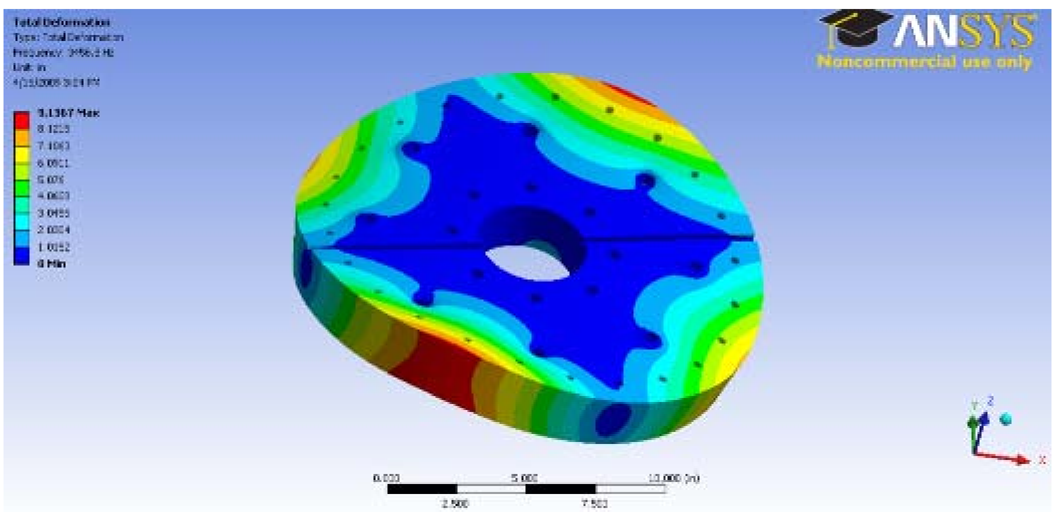


Figure 18. NPSCuL-Lite structural test fixture, third mode ~3455Hz

The first two modes reported by the analysis software occur at nearly the same frequency, 3280 Hz, and show the similar deformations. The second pair of modes reported by the software occur at about 3455 Hz, and again show similar deformations, though these modes are clearly different from the first two. These results more than satisfied the requirements for testing, and the fixture was constructed as designed.

## C. NPSCUL-LITE STRUCTURAL TEST

### 1. Construction of the NPSCuL-Lite EDU

Inter-City Manufacturing of Sand City, CA manufactured the components of the NPSCuL-Lite qualification article in April, 2009. Construction took place in May 2009. The structure consists of 4 wall plates, 4 angle brackets, a base plate, and an adapter ring which connects the structure to the secondary payload adapter via a standard interface. It is designed to carry eight P-POD Mass Models or P-PODs using a standard 6-bolt rectangular pattern. For the qualification tests, one wall was modified to carry a mass simulator of the sequencer electronics package. The structural design engineer created an instruction manual and a formal construction procedure document to aid in construction, using the P2M2 construction procedure document as a template.

Figure 19 depicts an exploded view of the NPSCuL-Lite EDU structure. Figure 20 shows the coordinate system used for NPSCuL-Lite design and testing. The coordinate system is matched to the coordinate system used for the ABC payload adapter.

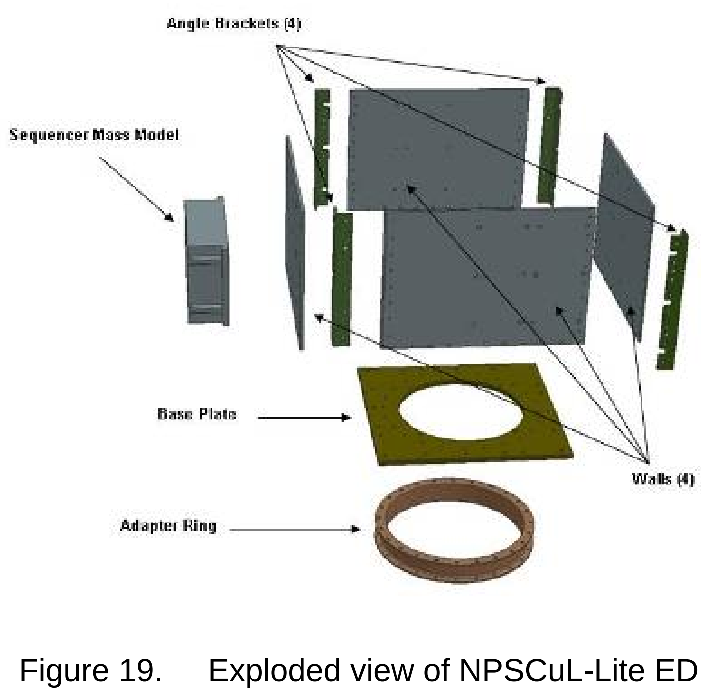


Figure 19. Exploded view of NPSCuL-Lite EDU

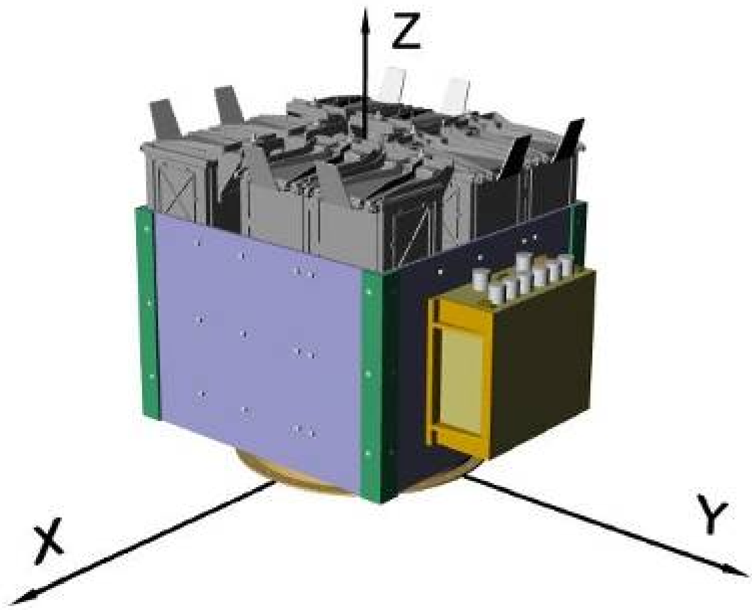


Figure 20. NPSCuL-Lite coordinate system

### 2. Finite Element Model Analysis

Daniel Sakoda created the preliminary finite element model (FEM) for the NPSCuL-Lite structure using the I-DEAS computer aided design and simulation software package. This software uses a graphical interface to create a mathematical model of a structure based on its geometry and material properties using various “element types” to describe how the components of the structure react to input forces. The FEM for NPSCuL-Lite was a simplified two-dimensional representation of the structure’s walls, base plate, and adapter ring, based on the dimensions included in the production drawings. Beam elements were used to connect the walls together, simulating each fastener in the angle brackets. The P-PODs were simulated using three lumped-mass elements, each with one-third the mass of a P-POD. These lumped-mass elements were positioned according to a P-POD’s expected center of mass, connected to each other using rigid body elements, and then each lumped mass element was connected to the wall in two places using rigid body elements (six connections

per set of three lumped mass elements). Boundary conditions for the simulation were applied at the 24 nodes of the bolted interface, fixed in translation but free in rotation. A depiction of the model is shown in Figure 21.

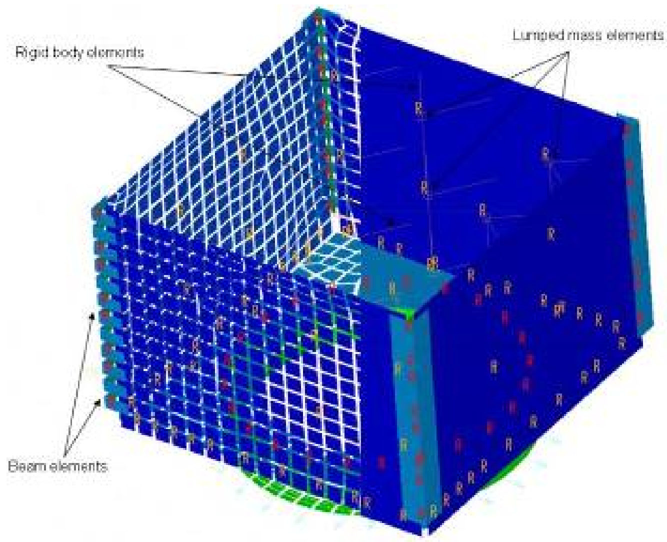


Figure 21. Graphic display of preliminary NPSCuL-Lite finite element model

Modal analysis of the FEM was performed to reveal the expected dynamic characteristics of the NPSCuL-Lite structure. As stated in Chapter II, the launch provider required full characterization of all modes below 100 Hz. To achieve this, the NPSCuL Team developed the preliminary FEM with the intent of modifying it based on the experimental data from the qualification tests.

Independent of the qualification-testing schedule, it became apparent that a miscommunication had occurred between the NPSCuL Team and the launch provider. The result of this miscommunication was that ULA had assumed, for the purposes of the launch vehicle CLA, that ADaMSat would have no modes below 100 Hz, while the NPSCuL Team considered 35 Hz to be the acceptable threshold for the fully-loaded structure. ULA had already completed a significant portion of the CLA work by modeling ADaMSat as a simple mass with no dynamic input to the rest of the rocket, and they now realized that this work would have to be repeated using the actual modal characteristics of ADaMSat.

So, the preliminary FEM had to be submitted “as-is” to the launch provider to support NROL–41 Centaur coupled loads analysis. This FEM is described in detail below.

The first mode (Figure 22) of the model occurs at 51 Hz, and involves bending of the base plate of the structure.  This bending results in the walls deforming from square to a roughly parallelogram shape, as shown in Figure 22. Note that each wall is also bent, such that they are alternately convex and concave in the area where the P-PODs are attached.  Identification of this mode shape helped to characterize one of the possible failure modes described in Section 4 of this chapter.

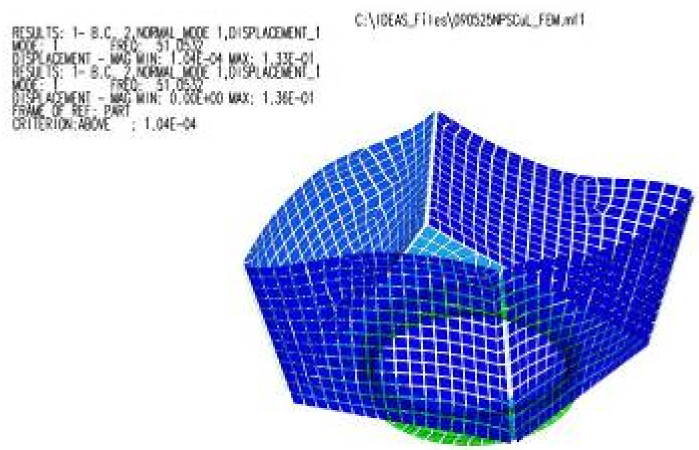


Figure 22.     NPSCuL-Lite FEM, first mode (51 Hz), bending of the base plate

The second and third modes occur at approximately 63 Hz and involve rocking of the base plate on top of the adapter ring in alternate directions. (Figures 23 and 24).  The fourth mode in the model occurs at approximately 100 Hz and involves bending of the base plate in the NPSCuL-Lite Z-axis, around the adapter ring (Figure 25).

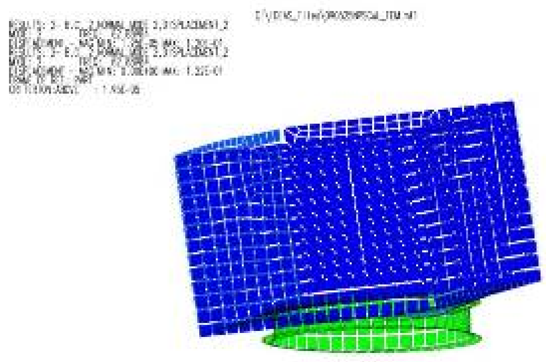

Figure 23. NPSCuL-Lite FEM, Mode 2 (63 Hz), rocking motion

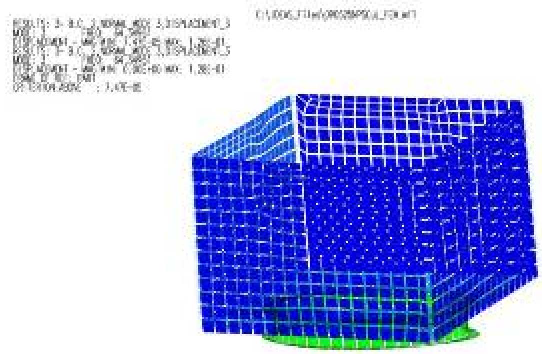

Figure 24. NPSCuL-Lite FEM, Mode 3 (64 Hz), rocking motion

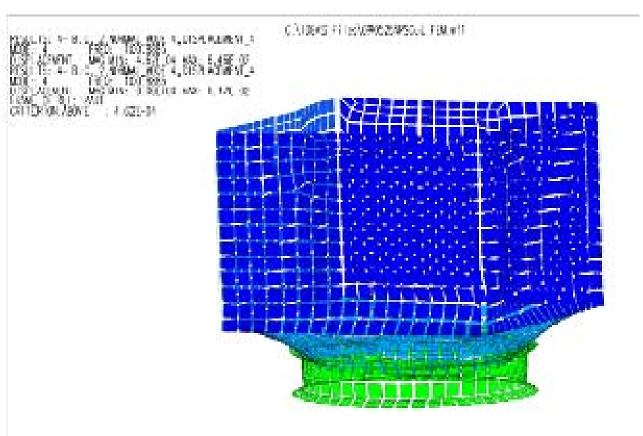

Figure 25. NPSCuL-Lite FEM, Mode 4 (101 Hz), base plate bending uniformly in the Z-axis

With the preliminary FEM complete, the NPSCuL Team went ahead with the first round of structural tests to produce conclusive data about the fundamental frequency of the structure, and verify the integrity of the design.

### 3. Structural Test Results

During initial testing of the NPSCuL-Lite vibration test fixture, the electrodynamic shaker at NPS malfunctioned and was rendered inoperative. Repair of the device was expected to take two weeks or more. The project was already behind schedule to complete the structural qualification (see Table 1) so the decision was made to use an industrial environmental test facility (Quanta Labs, Santa Clara, CA) to perform the tests. The terms of the fixed-price contract between the NPSCuL Team and Quanta Labs allowed no more than two days to complete testing in all three axes. This meant that independent testing of the fixture would not be possible. The NPSCuL-Lite EDU was integrated with P2M2s at NPS and then taken to Quanta for immediate testing, beginning with the Z-axis. Figure 26 shows the intended test flow for the qualification test battery. Figure 27 describes the standard naming convention for various components of NPSCuL-Lite and the numbered locations of each P-POD or P2M2, referenced throughout the test results.

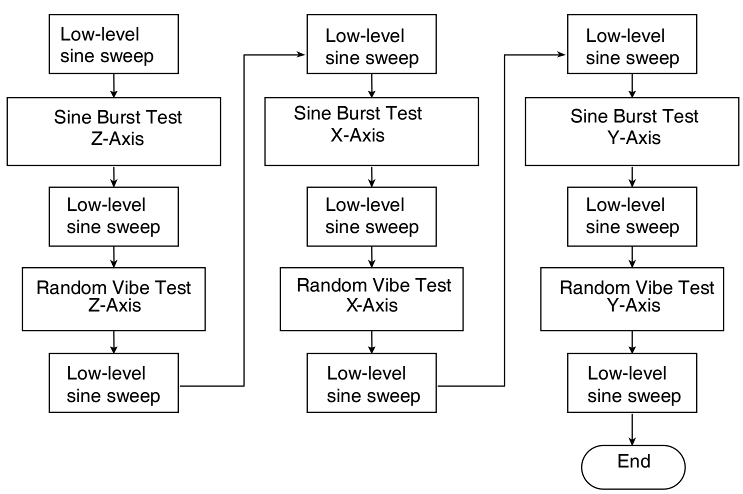


Figure 26. NPSCuL-Lite Qualification Test Flow

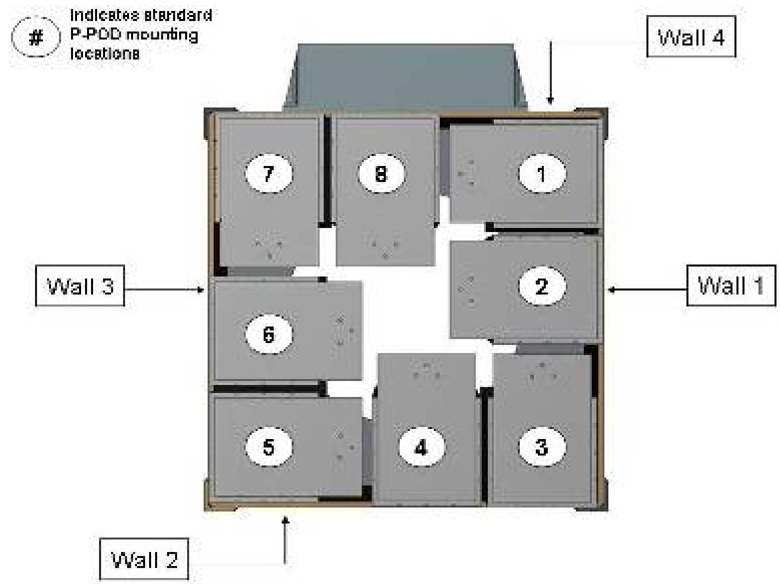


Figure 27. Wall numbering designations and standard P-POD/P2M2 mounting locations of the NPSCuL-Lite structure

Quanta Labs provided a Ling 300-series electrodynamic shaker with 8,000 lbf capacity. A slip table was provided so that the test fixture originally designed for the NPS shaker could be used for testing at Quanta in all three axes. A significant benefit to using a commercial facility was that a technician was provided to operate the equipment; this technician was also available to answer technical questions and assist with troubleshooting. The only limitation encountered was that there were only eight accelerometer channels available to the shaker. For this reason, the full complement of measurements described in the NPSCuL-Lite EDU Test Plan could not be taken; instead, a scaled-down placement scheme was implemented to provide a minimum characterization of the structure. As shown in Figure 28, the control accelerometer was placed on the test fixture. This was the preference of Quanta Labs, who wanted to ensure that the input was realistic. Though independent testing of the fixture was not possible, the analysis described in Section B of this chapter was considered sufficient to rule out any effect the fixture might have on the results.

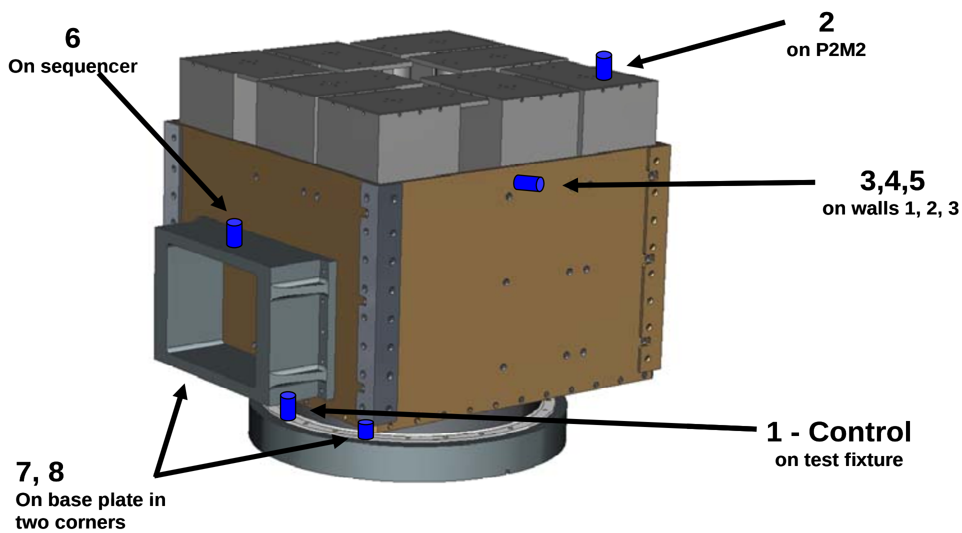


Figure 28. 8-channel accelerometer placement scheme for Z-axis structural test at Quanta Labs, May 2009. Numbers indicate measurement channels

Several anomalies were encountered during the test. One accelerometer (channel three) fell off the structure during the first sine sweep test, due to insufficient adhesive. It remained detached until it was reinstalled prior to the random vibration test, so data from that accelerometer was not considered accurate for any of the tests except the random vibration. A second accelerometer (channel eight) produced questionable data in the sine sweep and sine burst tests; the levels measured on this channel during random vibration test were even less plausible. The technician was able to test the electrical lines from the power conditioner to the accelerometer and determined that the electrical connection was faulty. The data obtained from this channel was also not considered accurate, and so it is not included for any of the tests described below. Since both accelerometers were taking measurements from redundant structural locations, the data presented below nonetheless represents a reliable characterization of the structure as designed. Finally, the technician who set up and operated the shaker misinterpreted the sensitivity values for some of the accelerometers; as a result, some channels produced data that were an order of

magnitude lower than expected. Quanta Labs was able to deliver the data in a spreadsheet format that could be adjusted mathematically after the test. The results given below include the corrections for this error.

The first sine sweep (results shown in Figure 29) revealed three significant low-frequency resonances at 60, 125, and 185 Hz. The apparent very low-frequency resonance at the start of the sweep did not appear in the second sine sweep, so it may or may not represent an actual resonance in the structure. The curves are largely symmetrical around the 125 Hz peak, indicating that similar modes are in effect at 60 Hz and 185 Hz. Nonetheless, it can be concluded that the structure is slightly more stiff than the structure represented in the FEM, with a fundamental frequency of 60 Hz vice 51 Hz. Note also that the response from channel five is significantly different from the other channels; it showed little response at the 60 Hz resonance, but clearly responded to the 125 Hz mode. This accelerometer was mounted on a different wall than the channel three accelerometer, and the accelerometers on these walls were orthogonal to the test axis. The low level of response may indicate that this location was a “null location” with regard to the 60 Hz resonance, but still responded to the 125 Hz resonance experienced by all other working accelerometers.

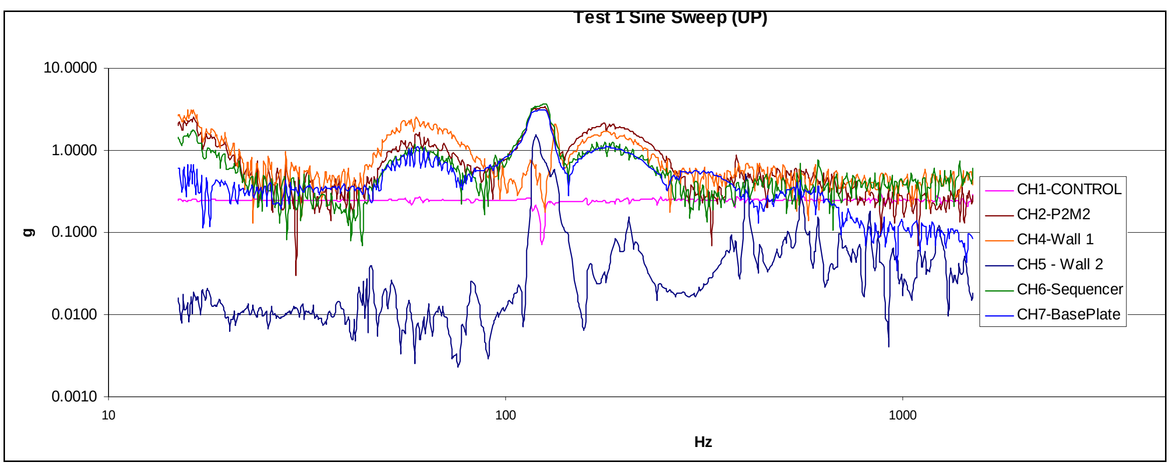


Figure 29. Test 1, sine sweep, NPSCuL-Lite Z-axis.

The second test (results shown in Figure 30) was a sine burst to impose quasi-static loads on the structure, in accordance with the ULA-provided loads and a factor of safety of 1.25. The only required data points for this test are to show that the input profile was successfully obtained by the control accelerometer; the two plots are closely matched at the target level of 12.4 g. Subsequent visual inspection revealed no anomalies, and the test schedule continued with a post-test sine sweep to see if there were any changes to the structures dynamic characteristics.

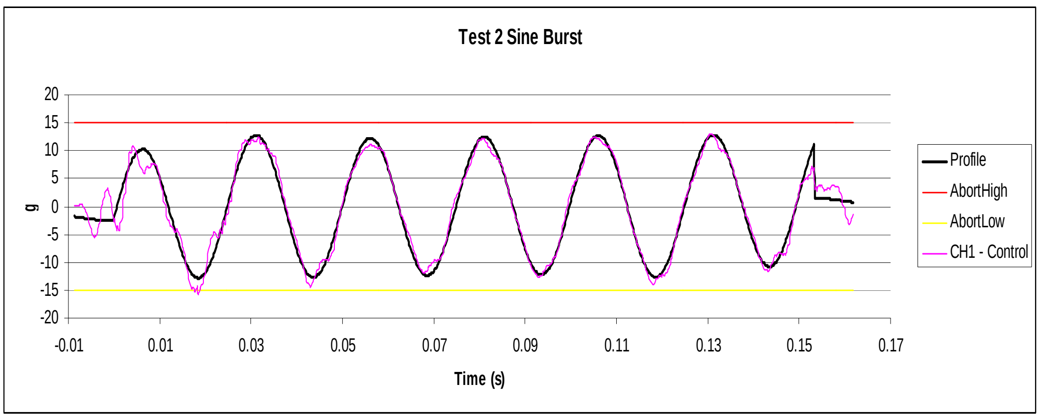


Figure 30. Test 2, sine burst, NPSCuL-Lite Z-axis

Results of the second sine sweep are shown in Figure 31. Note that the very low-frequency peak discovered in the first sine sweep did not appear in this test. Otherwise, the results are very similar, confirming that no significant change in the structure’s modal characteristics occurred as a result of the sine burst test.

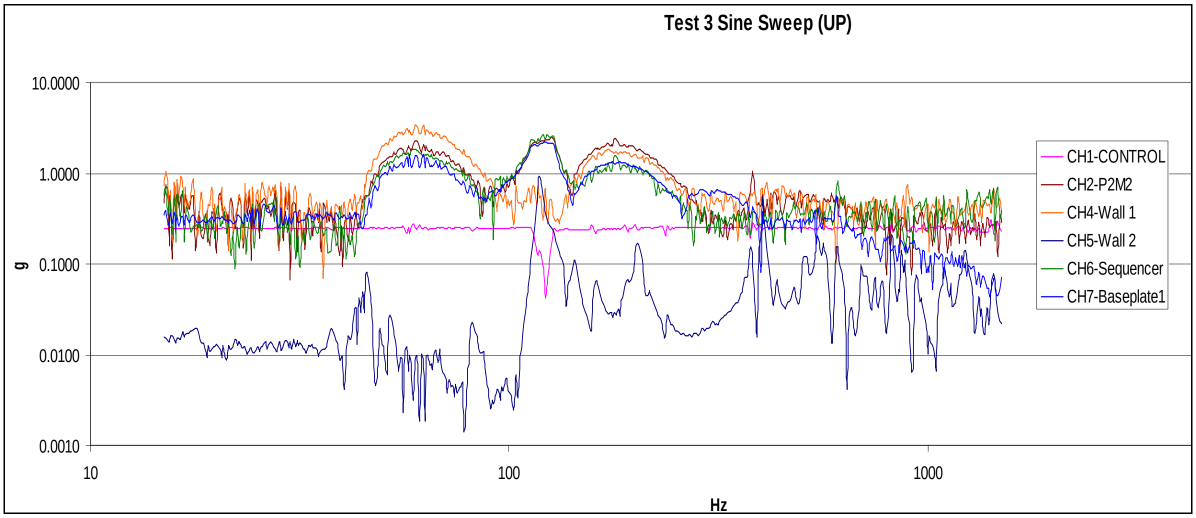


Figure 31. Test 3, sine sweep, NPSCuL-Lite Z-axis

Following the second sine sweep, the detached accelerometer on wall three was reattached. It provided reliable data throughout the Z-axis random vibration test. Unfortunately, the random vibration test was halted after 40 seconds at the 0 dB level due to a structural failure. The time-averaged output of the test, up to the manually commanded abort, is shown in Figure 32. The first peak occurs between 90 Hz (on the base plate) and 95 Hz (on the walls), and the highest ASD measurement is from wall two, which read 21.9 $g^2$/Hz at 95 Hz. Note that this accelerometer measured extremely low readings in the sine sweep tests. In future testing, it would be prudent to place an accelerometer on wall four (if a sufficient number of channels are available) to compare its response to that of the other three, to understand why this wall reacts differently from the other two walls under dynamic load conditions.

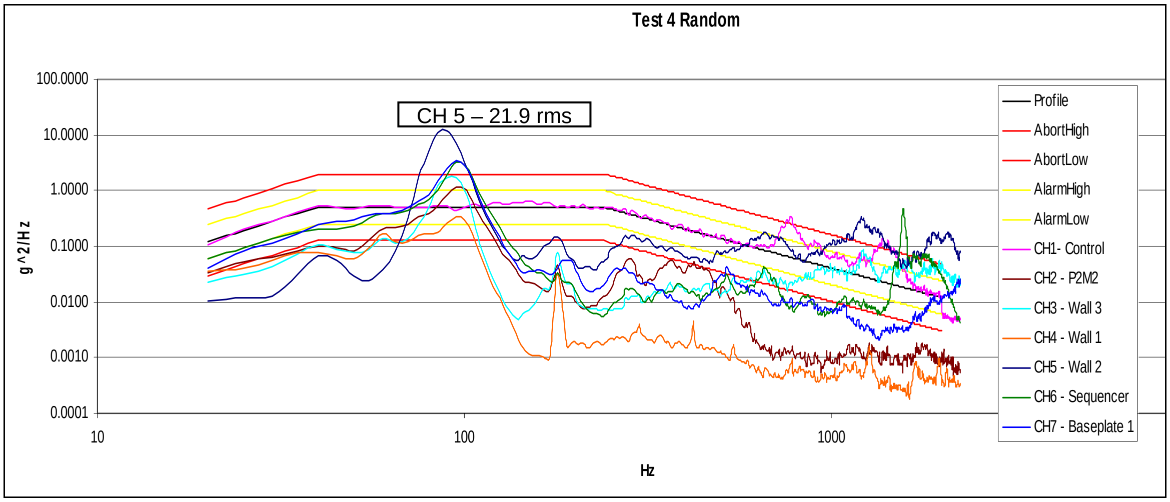


Figure 32. Test 4, random vibration, NPSCuL-Lite Z-axis, 0 dB level, 40 seconds duration

The only significant anomaly in the operation of the test was that the shaker was unable to maintain the defined profile of the test in the high frequency range (above 700 Hz). The control accelerometer peaked at 775 Hz and again at 1425 Hz, with amplitudes well above the test definition. When this abnormality was pointed out, the Quanta Labs technician explained that the dynamic characteristics of the NPSCuL-Lite structure were feeding back into the shaker's closed-loop system. For the sake of clarity, Figure 33 shows the results of the same random vibration test, with only the control channel measurements displayed.

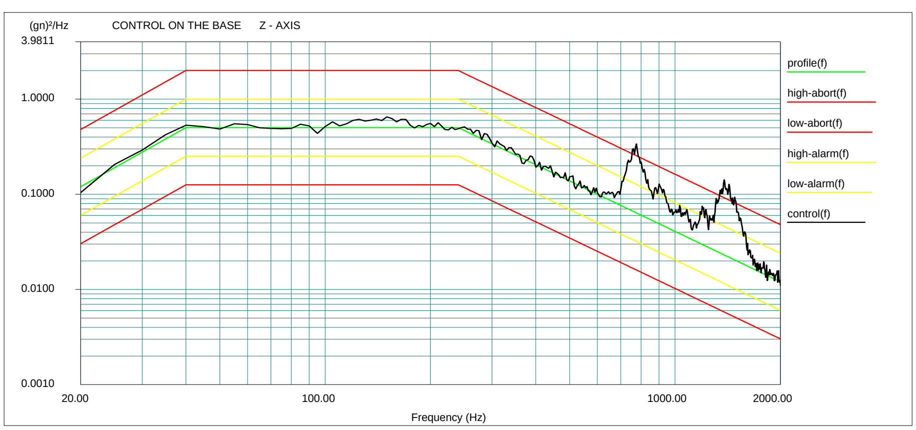


Figure 33. Test 4, random vibration, NPSCuL-Lite Z-axis, 0 dB level, 40 seconds duration, control channel only

Recall the results of the P2M2 random vibration tests in Chapter II. During these tests, there were spikes in the control channel, which could not be clearly explained. It is apparent that the control channel spikes above the desired test level due to coupling between the article under test and the shaker. Evidence for this is that the drive voltage from the vibration controller PC to the shaker drops to zero at corresponding frequencies, so the whole shaker/fixture/test article system is producing the vibrations regardless of any apparent electrodynamic input from the shaker at those frequencies. The gain of the shaker can sometimes be adjusted to reduce this effect, but it could not be eliminated in any of the testing performed by the NPSCuL-Lite program to date. What remains unknown, then, is whether the fixture or the shaker itself can be modified to prevent this anomaly. The qualification test random vibration environment for ABC (based on the ABC maximum predicted envelope) is very severe, even when compared to those of other secondary payload environments. For whatever reason, the vibration control loop is unable to reproduce the desired acceleration spectral density vs. frequency spectrum, regardless of the configuration of the article under test or the test fixture. The cause of this phenomenon remains open for further investigation (see Chapter V).

## D. STRUCTURAL FAILURE OF NPSCUL-LITE IN THE RANDOM VIBRATION ENVIRONMENT

### 1. Events and Observations

After about 30 seconds at the 0db level in the random vibration test, the screws holding one of the P2M2s (P2M2 #105) on NPSCuL-Lite began to back out. Within 8 seconds, all six screws had either backed out, or been forced out, by movement of the P2M2. The test was halted at this point in order to see if there was any significant damage to either NPSCuL-Lite or the P2M2.

Upon inspection, NPSCuL-Lite showed no significant damage. There were witness marks on the inside of the wall, where the edges of the P2M2 made contact. All screw clearance holes were intact. Five of the six screws that held

the P2M2 were recovered, but all showed only normal expected wear on the threads. Two of the P2M2 mounting points suffered significant damage: The last two screws to disengage the P2M2 had pulled the threaded inserts out of the installation holes, and these holes were somewhat elongated. The other four holes appeared undamaged, which would be expected because the screws in these holes merely backed themselves out under vibration. A video camera clearly recorded the sequence of events as the connections failed, and it is apparent that four of the screws backed out, one by one, leaving only two partially-loosened screws to support the P2M2. The P2M2 continued to vibrate for at least one second while attached by only these two screws; it is likely that the elongation of the screw holes occurred at this time. The elongation of the screw holes caused the screws to pull out. Figure 34 shows the damage caused by this failure.

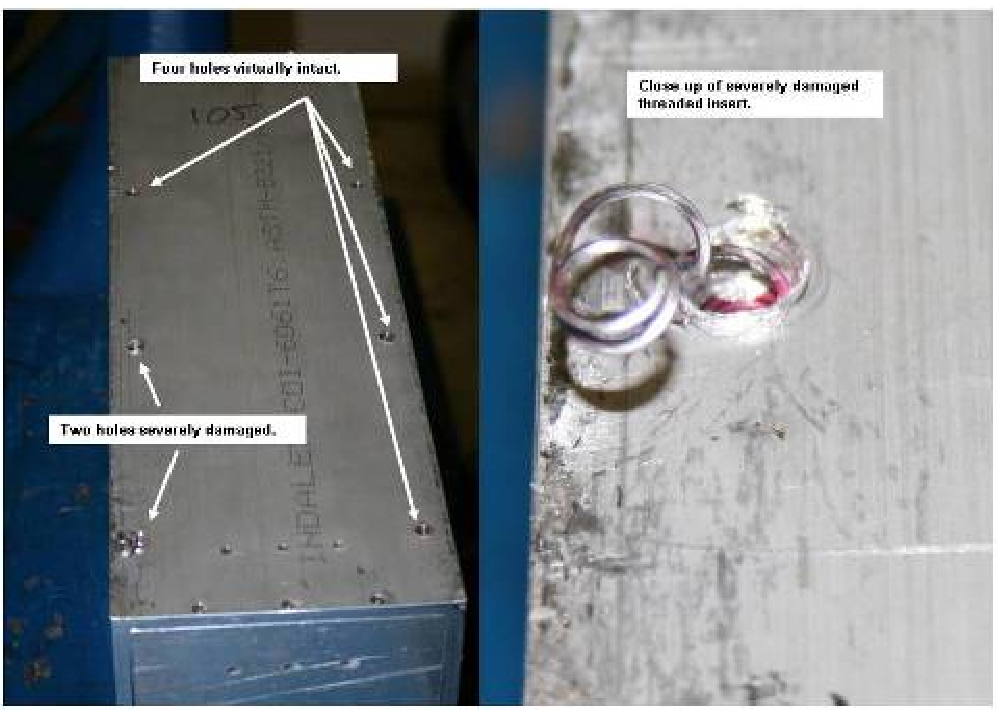


Figure 34. Damage to P2M2 #105 after 40 seconds at 0 dB level, random vibration test.

During this break in the testing, the technique for mounting the P2M2 to the NPSCuL-Lite EDU was modified to prevent the screws from backing out by replacing them with drilled-head socket cap screws and washers, and applying safety wire to the screw heads. The failed P2M2 was replaced with the original P2M2 engineering unit (P2M2 #001), and a second attempt was made at completing the Z-axis random vibration test that same day. After about 30 seconds at 0 dB, anotherP2M2 (P2M2 #102) appeared to be unconstrained and vibrating independently of the structure. A few seconds later, this P2M2 became completely detached from the structure and the test was halted a second time. In this case, the video camera was unable to capture the failure. However, a brief inspection of the safety wired fasteners indicated that the screws had not rotated significantly during the test. The damage to all six mounting points on P2M2 #102 was severe: all six screw holes were significantly elongated and several threaded inserts had been pulled completely out of these holes. Further testing on the structure was cancelled pending analysis of the failure.

### 2. Analysis Concerning Failure of Fasteners on NPSCuL-Lite

Chambers identifies three basic failure modes for threaded inserts: shear failure of the insert's internal threads, shear failure of the insert's external threads, and shear failure of the parent material's internal threads.[19] As shown by Chambers, using AL6061 as the parent material and all other things being equal, the third failure mode occurs under the lowest ultimate load. Both P2M2s experienced the third failure mode, to some degree, as discussed below.

In the first test, P2M2 #105 became disconnected from the wall because four screws backed out. There was no actual failure of the threaded inserts in these four holes. However, the last two screw holes were significantly damaged. As shown in Figure 34, the threads of the insert pulled from the parent material. A close look at the two damaged holes revealed that there was significant wear

19 Jeffrey A. Chambers, "Preloaded Joint Analysis Methodology for Space Flight Systems" National Aeronautics and Space Administration, 1995, 21.

of the parent material (aluminum), which allowed the screw to pull the insert partially out of the hole. This in turn caused the insert to unravel and release the screw.

In the second test, P2M2 #102 became disconnected because all six screw holes failed, according to the same threaded insert failure mode. Here, the post-test investigation found the parent aluminum around all six holes severely worn, and some portion of the threaded insert was still attached to some of the fasteners. Since the fasteners were constrained from rotating by the safety wire, it was impossible for them to back out (as happened on P2M2 #105). Instead, these fasteners pulled the threaded inserts out of the holes, due only to the wear on the parent material.

The two P2M2s became disconnected from the walls of the NPSCuL-Lite structure in two different ways. In the first failure, characterized by what happened to P2M2 #105, the parent material around the threaded insert failed subsequent to several fasteners backing out. In the second failure, characterized by what happened to P2M2 #102, the parent material failed around all of the fasteners, with none of them backing out prior to the first threaded insert failure. With two different failures identified, it was apparent that multiple issues had to be addressed before moving on with the structural test. The main issues were insufficient preload on screws out, the flatness of the interface surfaces, and the extreme dynamic environment prescribed for the test.

Two separate design elements were present in the bolted connections between the walls of NPSCuL-Lite and the P2M2 to prevent the screws from backing out: a locking threaded insert, and applied torque (pre-load). Threaded inserts were used in all of the screw holes in NPSCuL-Lite, and in the joint between NPSCuL-Lite and the P2M2, because the components are made of aluminum, which is a softer metal than the steel screws. If this joint were comprised of steel screws going into threads cut in bare aluminum, there would be a risk of damage to the threads during installation, especially if the screws had to be removed and reinstalled several times. Threaded inserts provide a more

reliable joint than tapped holes because the screw turns inside the (non-moving) insert, rather than against the softer aluminum threads. Self-locking inserts were chosen as a means of preventing the screws from backing out under vibration; these inserts include one or more non-circular elements that deform when engaged by a screw. This deformation causes the insert to exert a force on the screw thread, increasing the coefficient of friction between the threads and the bolt. In effect, a locking threaded insert “grips” the screw.

Bolt preload is the tensile load in a bolt or screw after it is tightened; it is the result of applying additional force to tighten a bolt (or screw) after the bolt head makes contact with the surface of the part to be joined, resulting in compression of the mating parts and elongation of the bolt.[20] Preload is applied to ensure that the parts to be joined remain in contact, even under external loads. As long as the external loads are less than the preload, there will be no movement of the bolt or the parts in contact. Any joint can be compromised, however, if the external force exceeds the preload; the goal of a fastener analysis is to ensure that sufficient preload is applied to prevent failure of the joint under the static and dynamic forces encountered in use. For screw joints, the design preload is commonly converted into a *torque value* that is applied to the head of the screw using a torque wrench. The simplest equation for calculating an applied torque value is

$$T = KDP_o$$

where T is the applied torque, D is the nominal bolt/screw diameter, and $P_o$ is the desired preload. In this equation, K refers to a unitless “nut factor,” which results from friction between the threads of the bolt and the threads of the nut. Values of K typically range from 0.12 to 2.0, depending on the material properties of the nut and bolt, and whether lubricants or locking compounds are applied to the threads.[21]

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20 Jeffrey A. Chambers, “Preloaded Joint Analysis Methodology for Space Flight Systems” National Aeronautics and Space Administration, 1995, 3.

21 Ibid., 4.

The preload on a screw can become relaxed due to several factors including embedment, environmental factors, and self-loosening due to vibration.[22] Embedment is deformation of the contact surface at the joint, and most commonly happens during installation; the applied torque does not result in the desired preload because the surface under the bolt deforms, and tension in the bolt relaxes after the torque is applied. Embedment can also happen over a period of time if the materials deform slowly.[23] Environmental factors such as thermal expansion/compression can affect the length of the bolt and thereby reduce the tension in the bolt. Finally, vibration forces can reduce the coefficient of friction between the bolt threads and the nut threads; as the joint vibrates, differential forces are applied to the nut and the bolt, causing them to move independently.

In the failure analysis, the NPSCuL Team determined that most of the fasteners holding the NPSCuL-Lite structure together were installed with insufficient preload. Following the failure, the entire structure was examined using a torque wrench to tighten each fastener, and the torque values at which the screws began to turn was recorded. A large number of fasteners were found to have less applied torque than when they were initially installed, and this result was attributed to the vibration test environment. The dynamic forces on the components during the test overcame the preloads on the screws; in this condition, there was little or no friction between the screw threads and the screw thread inserts. The self-locking feature of the screw thread insert was insufficient to prevent the loss of preload on the screw. This issue, by itself, does not fully account for the failure of the fasteners at the wall/P2M2 interface, but it was likely a contributing factor.

22 Jeff Jungmann, “Threaded Fasteners Seminar: Preload Loss and Vibration Loosening” (presentation to SAE 2009 Brake Colloquium) http://www.sae.org/events/bce/presentations/2008jungmann.pdf (accessed 4 June 2009).

23 Jeffrey A. Chambers, “Preloaded Joint Analysis Methodology for Space Flight Systems” National Aeronautics and Space Administration, 1995, 12.

The most significant cause of the P2M2 fastener failure was that the face of the P2M2 that abutted the wall of NPSCuL-Lite was not flat. The main body of the P2M2 was constructed out of a length of extruded aluminum tube. The extrusion process used to form the tube did not produce a perfect square; instead, the tube was slightly concave or convex in varying places along its length. The design of the P2M2 called for flattening of the face in which the screw thread inserts were to be installed; this was done on P2M2 #001, but it was not done in the production run (P2M2s #101–#108) and is considered a manufacturing defect. Evidence that all eight production-run P2M2s were insufficiently flat was found on the walls of NPSCuL-Lite during the post-test investigation. As shown in Figure 35, witness marks run the entire length of the walls where the edges of the P2M2 made contact. Normally, witness marks would be expected not along the edges, but along the centerline of the screw patterns indicating that there was no gap between the P2M2 and the wall at the screw interface. This was, in fact, seen where P2M2 #001 was installed in position #5 during the second random vibration test. It is clear, therefore, that the overall concavity of the P2M2 caused the witness marks along the edges, and provides strong evidence that a gap existed at the fastener joint. It is thought that, under vibration, the size of this gap varied due to flexing of the structure, resulting in a loss of preload. As the test went on, these surfaces would have continued to flex, imposing a force on the screw head in the “loosening” direction.


Figure 35. Witness marks on the inside of Wall 1 of NPSCuL-Lite EDU, P2M2 positions 1 and 2

The gap between the surfaces explains the two P2M2 fastener failures. The vibrations caused a loss of friction between the threads, and caused slight relative motion between the threads resulting in further loosening of the screw. The forces causing the relative motion exceeded the static friction provided by the locking insert; it has been conclusively shown that the locking feature of the insert was not sufficient to prevent backing of the screw. In the first failure, the first four screws that failed merely followed the path of least resistance and backed out completely. The last two screws encountered a bending moment that deformed the screw holes and ultimately pulled the screws out of the holes. The "unraveling" of the screw thread inserts at these two joints shows that these screws did not back out, but were pulled out. In the second vibration test, the screw heads were safety-wired together to prevent backing. While safety wire can prevent screw heads from turning, it has no effect on the relaxation of preload on the screw under applied forces. The axial loads on the screws during

the vibration did not result in the failure, because the screws could not rotate. But, with the gapping between the surfaces, shear loading on the screws caused them to wear against the inside of the screw clearance holes in the wall, and ultimately deform the clearance holes. As the clearance holes became larger, the bending moments on the fasteners increased, ultimately causing all six fasteners to pull out of the holes similarly to the last two screws of P2M2 #105. Significant evidence was found for this failure mode: a large amount of aluminum dust was found on the shaker after the test, and the post-test investigation found every screw clearance hole at the position where P2M2 #102 was installed was elongated, primarily in the Z-axis direction. Inspection of P2M2 #102 revealed that the threaded insert installation holes were deformed, primarily in the Z-axis direction, as well.

Another issue was identified, which may have been a contributing factor in the fastener failure: bending of the wall due to the shape of the dynamic modes. For example, the first mode (as shown in the FEM analysis) caused the base plate to bend up or down over the adapter ring, with diagonally-opposed corners in phase. This resulted in the walls deflecting out of square, and becoming bent. This bending could result in application of differential forces on the six P2M2 screw joints. Repeated cycling of these forces over time could contribute to loss of preload, gapping between the mated surfaces, and elongation of the screw clearance holes. It is conceivable, however, that even with the surfaces machined to a high degree of flatness, and sufficient preload, the fasteners might still fail due to bending of the walls under severe dynamic environments.

Aside from the NPSCuL interface issues, the post-test investigation revealed a continuing problem with the P2M2. On five of the seven undamaged P2M2s, the screws connecting the back plate and the center rod were found loose. The staking compound used on these screws was insufficient to prevent the screws from backing. It is believed that the issue here is the same as the issue with the NPSCuL-Lite structural component assembly procedures:

insufficient preload on the screws. Since all of these screws are high-quality steel, they can likely withstand significantly more preload than is currently specified.

The post-test investigation concluded with three items open for action prior to resuming testing. First, a thorough fastener analysis needs to be performed to ensure sufficient preload on every fastener in the structure, and additionally on the P2M2 structures. Second, the P2M2s need to be remanufactured with a specific flatness specification on the mating face. Finally, analysis will be done on the FEM to try to increase the stiffness of the overall structure. Further details on conclusions and recommendations are given in Chapter V.

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# IV. NPSCUL-LITE LAUNCH VEHICLE INTEGRATION

## A. LAUNCH VEHICLE INTEGRATION REQUIREMENTS

### 1. ADaMSat Overview

The NPSCuL development program is as much about processes as about building space-qualified hardware. NPSCuL-Lite has to provide a safe and reliable interface to attach P-PODs to the ABC secondary payload adapter. But beyond this requirement were the multitude of requirements to ensure that NPSCuL-Lite, the sequencer unit, the P-PODs, and the customer-developed CubeSats would meet the safety, environmental, and non-interference demands of launch on a yet-untested upper stage component. For this reason, the NPSCuL-Lite team began direct consultation with the launch provider (ULA) at the earliest stages of planning. Integration planning was conducted concurrently with the qualification testing described in Chapters II and III of this thesis in order to meet the needs of the launch provider.

The term "spacecraft integration" is ambiguous because of the complex nature inherent in space launch operations. "Integration" may refer to the assembly and test of the various components of a single spacecraft, or to the mating of the spacecraft to the launch vehicle. In the case of NPSCuL-Lite, a third sense of the term "integration" became meaningful: the assembly of the NPSCuL-Lite structure with the sequencer, eight P-PODs, and eight CubeSat payloads which, at the time, were under development with zero visibility from the NPSCuL Team. As of June 2009, the program sponsor is actively seeking a contractor to serve as a "mission integrator," with comprehensive integration responsibility for the NROL-41 secondary payload. In the context of an informal telephone conference in April 2009, the sponsor announced the official "mission nomenclature" which NPSCuL-Lite would support: the Advanced Science & Technology (AS&T) Development and Maturation Satellite, or ADaMSat. This

was not merely a name-change. By referring to all the components of the first ABC payload (collectively) as ADaMSat, and by identifying a single office responsible for both internal integration and launch vehicle integration, the process would be streamlined and simplified to the benefit of all involved agencies.

For the remainder of this chapter, the term ADaMSat will refer to all flight hardware related to the NROL-41 ABC launch, including: NPSCuL-Lite structure, NPSCuL-Lite electrical harness, P-POD deployment sequencer, eight Cal Poly P-PODs (Mk III), and the CubeSats slated for launch. This nomenclature was accepted by all the stakeholders involved in the launch, including NPS, ULA, NRO, Cal Poly, the Office of Space Launch (OSL) which managed the manifest, and Aerospace Corporation, who provided safety and operational oversight of the mission.

## B. GROUND HANDLING AND TRANSPORTATION

The ground handling of a spacecraft, up to and including the process of attaching the spacecraft to a launch vehicle, requires strict attention to detail and thorough planning. The engineers and planners who develop the spacecraft design concepts may be tempted to write off these considerations as merely routine or ordinary, and may overlook critical requirements in this area. However, any anomalous event that occurs during ground handling and transportation can have devastating effects on the program. Additionally, the structural loads and vibrations encountered during spacecraft ground transportation may be as severe, or worse, than those experienced by the spacecraft during launch. Early and continuous attention paid to the ground handling environment of the spacecraft pays huge dividends in terms of mission success.

In the absence of a designated ADaMSat mission integrator, the NPSCuL Team helped with launch vehicle integration. At the ABC “kickoff” conference in December 2008, a ULA representative presented a notional concept of

operations for the integration of ADaMSat with the Centaur upper stage. While the timeline for the operation was still very much unknown, ULA described the order of events in sufficient detail to allow the NPSCuL Team to begin a few necessary design modifications. The initial processing flow for a generic secondary payload (SP) integration was as follows:

1. Secondary Payload (SP) arrives at launch integration site
2. SP unpacked from shipping container. Vertical lift as necessary.
3. SP vertically integrated to ABC
4. SP/ABC rotated 90 degrees to allow integration with Centaur (while Centaur is still horizontal and still in its shipping container).
5. SP/ABC horizontal integration with Centaur
6. Centaur rotation and integration on the Atlas stack

The vertical lift involved in step 2, and the rotation involved in step 4, were generic considerations for a generic ABC payload that would deploy *in toto* from the ABC, using a Lightband or other similar deployment mechanism. ADaMSat did not require a deployment mechanism because it possessed its own means of deploying individual satellites, and there was no requirement to separate ADaMSat from the ABC. The launch provider understood this difference and agreed to integrate the ADaMSat /ABC combination in the horizontal orientation. This meant that all handling processes at the launch integration site would be accomplished with ADaMSat horizontally-oriented, simplifying the problem for the launch provider.

But it did not simplify the problem for NPSCuL-Lite. The structure is most symmetrical about the Z-axis; while fully loaded with CubeSats and P-PODs, the easiest way to transport it is in the vertical orientation. So, the spacecraft would have to be rotated from vertical to horizontal at the launch vehicle integration site. Many spacecraft (including large spacecraft, like the Space Shuttle) accomplish required 90-degree rotations using a *breakover fixture*: a piece of ground support

equipment with the sole purpose of providing a safe rotation. The NPSCuL Team, while discussing this issue, realized that a viable breakover fixture was immediately available: the Get-Away-Special (GAS) dolly.

The Get-Away Special program was an STS (Space Shuttle) space-access solution that ran from the mid-1980s until the Columbia disaster in 2003. Like the CubeSat program, it enabled the launch of educational and scientific payloads using a standardized interface, called a GAS Canister, which could frequently ride-share in the Space Shuttle Cargo Bay. The GAS Canisters housed completely independent, recoverable payloads; the HitchHiker program was based on the GAS Canister structure, but depended on the Space Shuttle for power and commands. Some HitchHiker payloads were actually deployable; notable among these was the first satellite launched by the Naval Postgraduate School, the Petite Amateur Navy Satellite (PANSAT). Figure 36 shows PANSAT mounted on the GAS dolly, which is described in further detail below.

Figure 36. PANSAT handling on GAS dolly, 1999 (From [24])

Goddard Space Flight Center developed the design specifications for the GAS/HitchHiker programs, and produced much of the hardware to support them.

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24 Daniel J. Sakoda, "The Petite Navy Amateur Satellite (PANSAT) Hitchhiker Ejectable, (Presentation, Shuttle Small Payloads Project Symposium, September 1999).

When NPS built PANSAT, they procured a GAS dolly from Goddard to support testing and integration. The GAS dolly is a ground-support handling fixture designed to fit the GAS Canister form factor, and provides for floor-rolling transport, forklift pickup, crane pickup, and up to 90 degrees of rotation in one axis. Fortunately, the GAS dolly was maintained by NPS after PANSAT's launch; it was planned for use by the second NPS satellite, NPSAT1, and turned out to be well-suited to the NPSCuL-Lite program. ADaMSat fits comfortably in the volume confines of the GAS dolly and is well within the weight and CG limitations of this device.

Under the assumption that the GAS dolly, or a similar ground handling device, could be used for delivery of ADaMSat to the launch integration site, and given that only horizontal lift was required, the processing flow for ADaMSat was altered as follows:

1. ADaMSat arrives at launch integration site
2. ADaMSat unpacked from shipping container and rotated by the GAS dolly. Handling fixture lifts ADaMSat in horizontal orientation.
3. ADaMSat horizontally mounted on mate fixture. ABC mated to ADaMSat.
4. ADaMSat /ABC transported to Centaur Integration area.
5. SP/ABC horizontal integration with Centaur.
6. Centaur rotation and integration on the Atlas stack.

Vertical lift was still an issue for NPSCuL-Lite. While the structure could be qualified without vertical lift, because the NPSCuL-Lite structure could be lifted manually, with or without the P-POD mass models installed, the same was not necessarily true of the flight article. Additionally, a suitable shipping container will be required to ensure a fully integrated ADaMSat can be shipped to the launch site without damage. As of this writing, these issues remain as open items for the integration contractor to address.

## C. INTEGRATION WITH CENTAUR UPPER STAGE

United Launch Alliance was responsible for procuring all required ground support equipment to handle ADaMSat from its arrival at the integration facility through integration with the Centaur. This included two uniquely designed items: a mate fixture, which would support ADaMSat during mating with the ABC, and a lifting device to carry the ADaMSat /ABC combination and position it properly for integration using an overhead crane.

### 1. ADaMSat Horizontal Lifting Fixture

The horizontal lifting fixture provides a means of handling ADaMSat (with or without ABC attached) using an overhead crane or other lift device. Initially, ULA requested threaded bolt holes installed on the outside of the NPSCuL-Lite structure; the walls and corner brackets, however, are too thin to provide adequate thread engagement. This led to the current design that involves four rods with pads that can grip the structure without a bolted interface. With ADaMSat in the horizontal position on a breakover device (such as the GAS dolly), the lifting fixture can be set flush against the wall opposite the sequencer unit. The rods are then rotated 90 degrees about the vertical axis so that the pads can engage the corner brackets on ADaMSat. Nuts on the rods are used to push the pads down against the structure and ensure the weight of ADaMSat is transferred evenly to the crane. Four pins on the lifting fixture engage four unthreaded .260 in. diameter holes in the NPSCuL-Lite structure; these pins do not carry any weight, but are provided merely to prevent ADaMSat from any sideways movement while it is lifted or rotated. The crane hook point can be repositioned approximately 3 inches forward or aft (in the Z-axis of ADaMSat); this allows a technician to accurately place the hook point over the center of gravity of the payload with or without ABC attached. Figure 37 shows ADaMSat with the lifting fixture engaged.

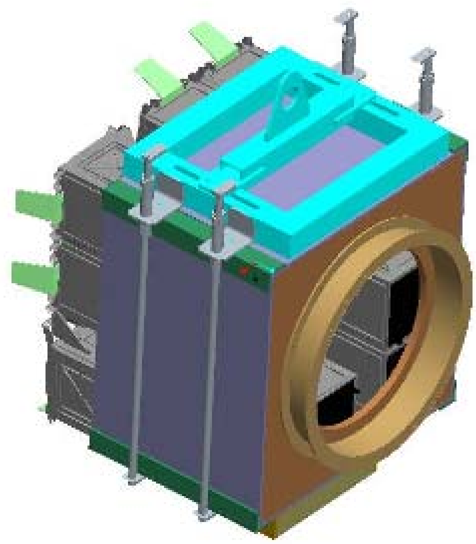

Figure 37. ADaMSat Horizontal Lifting Fixture

The NPSCuL Team performed a static loads analysis of the structure to ensure the lifting fixture will be able to engage ADaMSat with sufficient preload to keep the lifting rods engaged on ADaMSat without excessively deforming the structure. The only complication involved is that the preload will change when the assembly is lifted; unlike a bolted connection, where preload provides tension that tends to lengthen the bolts, the preload on the lifting rods will compress the rods. When the fixture is lifted, the weight of ADaMSat on the lower pads will tend to release some of the compression, changing the preload and reducing the force of friction between the upper pads and the surface of ADaMSat. So, the static loads analysis includes two situations: with the lifting fixture attached while ADaMSat is resting on a bench (or on the breakover fixture), and with the lifting fixture attached and the whole assembly under hoist. The analysis was performed iteratively by increasing the preload on the lifting rods in multiples of the total ADaMSat weight, until reaching the minimum preload where the assembly still showed some elastic deformation while under lift. For simplicity, the analysis was done on only one side of the NPSCuL-Lite structure, with the other side fixed in both translation and rotation. By using the full weight of

ADaMSat in the second situation, and confirming that the preload is sufficient, the results gain an automatic safety factor of two. The results of the analysis are presented here.

In the first situation (Figure 38), ADaMSat is assumed to be supported independently of the lifting fixture, as if it were sitting on the ABC mate fixture. The two rods are tightened to 340 lbf of preload, which is evenly distributed as a 170 lbf load at each of four places. The maximum deformation tolerable is assumed to be 0.010 inches, which is equal to twice the smallest manufacturing tolerance of the structure and would therefore not tend to affect any of the fasteners excessively. The resulting maximum deformation is $4.2 \times 10^{-3}$ inches occurring in the middle of the wall. The maximum equivalent stress is 937 psi occurring at the inside corner between the two walls. This is well below the compressive yield strength of AL 7075.

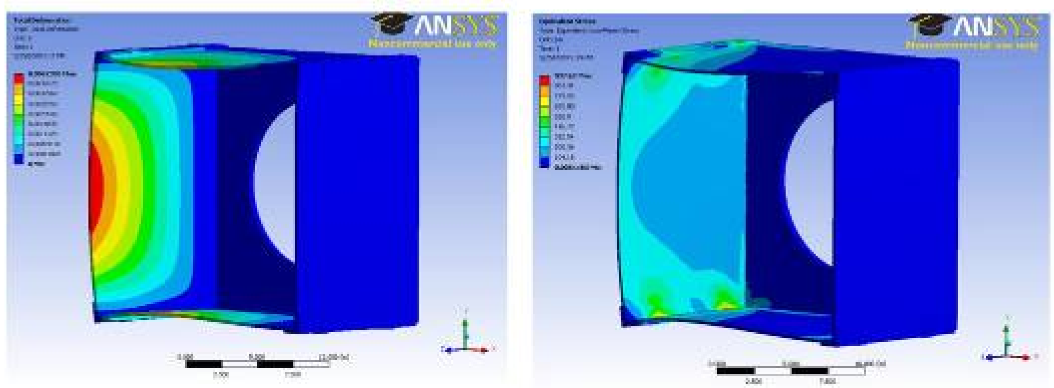


Figure 38. ADaMSat Lifting Fixture, first situation, 340 lbf preload on lifting rods

In the second situation (Figure 39), ADaMSat and the lifting fixture are under hoist. The two rods still maintain the same preload as in the first situation, but now the full 170 lbf weight of ADaMSat is applied to the lower angle bracket. In reality, the weight of ADaMSat would be distributed over all four pads more or less evenly, depending on whether the device is horizontal or rotated at some angle. Since the ADaMSat/ABC assembly will have to be rotated about 17 degrees out of horizontal during final Centaur integration, the analysis applies the

weight only to the angle bracket to provide a worst-case value.  As expected, the total compression of the structure is reduced; the resulting maximum deformation on the previously compressed wall is 3.8 x $10^{-3}$ inches.  The minimum equivalent stress around the pad engagement locations is 349 psi, so there is still some significant pressure on the structure to maintain friction and keep the lifting fixture engaged.

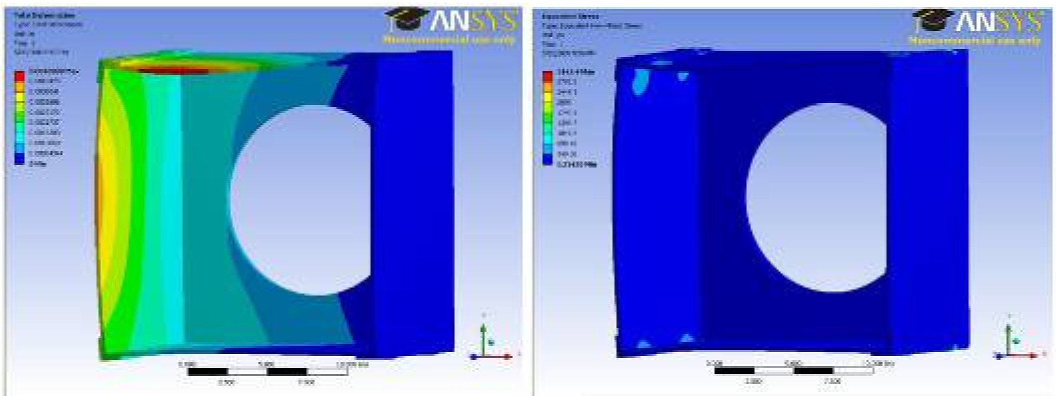


Figure 39. ADaMSat Lifting Fixture, second situation, 340 lbf preload on lifting rods with the weight of ADaMSat affecting the system

Assuming that the nuts and threads on the lifting rods can be treated as a standard bolted connection, and using K=0.2, D=.25 in., and $P_o$=340 lbf, the resulting torque value to be applied to the nut is 17 in-lbf.  These calculations do not include the weight of the ABC plate itself; this weight is estimated to be 16 lbf. Once the ABC plate design is complete, this analysis should be repeated with that mass included.  Ultimately, the torque value to be applied to the nuts on the lifting fixture will be at the discretion of the mission integrator and the launch provider.  With that in mind, this study provides an estimated minimum torque required.

### 2. ADaMSat/ABC Mate Fixture

The ADaMSat/ABC mate fixture serves as a workbench to support ADaMSat during integration with the ABC plate.  Once ADaMSat is placed on the mate fixture using the horizontal lift fixture, the hoist can be removed.  Integration

with the ABC plate will include (at a minimum) installation of 24 ¼”-28 socket cap screws from the adapter ring into ABC, and rigging of the electrical harness that connects the sequencer to the ABC secondary payload electrical interface. The horizontal lift fixture does not need to be removed from ADaMSat during integration because none of the bolted connections or wiring harnesses interfere with it.

The mate fixture design evolved concurrently with the evolution of the ADaMSat design. It began as a simple bench, and features were added along the way to minimize interference with the various components. Figure 40 shows the latest design concept as of May 2009. The large opening in the middle provides clearance for the sequencer, and allows ADaMSat to rest on the NPSCuL-Lite angle brackets only. The four smaller holes provide clearance for the lower pads of the lift fixture. In this design, it is difficult to impossible to access the sequencer connections, which is a problem since the electrical harness needs to be connected to the sequencer as part of the mate process. In the next iteration of the design, the NPSCuL-Lite angle brackets will rest on risers to allow the integration personnel full access to the sequencer connections. Continued participation in ULA’s ground support equipment designers will be critical to ensuring a smooth process flow at the launch site.

Figure 40. ADaMSat/ABC mate fixture (as of May 2009).

# V. CONCLUSIONS AND FUTURE WORK

## A. CONCLUSIONS

### 1. The NPSCuL Program

On May 25, 2009, NASA's PharmaSat (a 3U CubeSat) successfully completed its biological science mission.[25] This highlights the continued success of CubeSats and the capability of CubeSats to perform useful space missions at low cost. Development of NPSCuL as a high capacity CubeSat launch solution will enhance the utility and effectiveness of the CubeSat to do science, develop technology, and educate future space professionals. This development now hinges upon the success of the ADaMSat mission in 2010.

There have been delays in the NPSCuL-Lite development recently, due in part to difficulties encountered in qualification testing. The program as a whole, however, remains on schedule to deliver a ready-for-flight structure to the integration contractor in early 2010. Frequent interaction with the launch provider, ULA, and other interested parties has borne fruit, especially in the submission of documentation and development of the necessary ground support equipment for the mission. This cooperation can only be expected to improve as the critical milestones for the mission approach.

### 2. Vibration Testing of Spacecraft Structures

The NPSCuL Team had a limited understanding of structural dynamics testing methods at the start of this project. Because structure is such a critical part of the NPSCuL program, the team had to develop a knowledge and experience base with the hardware and software required for structural testing in

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25 "PharmaSat Operations Log," Santa Clara University, http://pharmasat.engr.scu.edu/OperationsLog.html (accessed 11 June 2009).

a very short time. By performing a full battery of tests, to full ABC qualification level, on P2M2 #001, the NPSCuL Team quickly developed the required expertise. This experience will continue to pay dividends for NPSCuL-Lite and the SSAG's other small satellite projects.

The environmental test requirements for secondary payloads on the ABC are significantly more challenging than the requirements for ESPA. Specifically, the severity of the random vibration environment at the qualification level requires extreme attention to detail to ensure that the structure survives the test. This includes fastener analysis, assembly procedures, accelerometer placement and test operation procedures. It should be noted that, to date, neither the Cal Poly P-POD nor the expected CubeSat payloads have been subjected to the ABC vibration environments. Anyone developing a potential secondary payload for the ABC must understand that the severity of this environment will affect every aspect of structural design, and design practices that were sufficient for other, less severe launch environments may not be sufficient for launch on ABC.

### 3. The Design Process for NPSCuL-Lite

The design process for NPSCuL-Lite relied heavily on the assumption that simplicity of design would ensure success. The term "simplicity of design" is used here to mean foregoing structural or mass optimization, or early detailed analysis, in favor of a simple structural design that maximized the available structural mass based on a payload complement of eight fully-loaded P-PODs. For example, the initial mass budget for NPSCuL-Lite was thought to be 200 lbm; in response to this maximum level, the structural designer modeled a structure that (along with eight P-PODs and a sequencer) weighed about 200 lbm. When the mass limit was reduced to 170 lbm, the walls were made thinner and the angle brackets were added to the corners to ensure good wall-to-wall attachment. This became a problem, however, after the first test; the failure to conduct finite element modeling and fastener analysis during initial design resulted in initial confusion during the post-test investigation. Specifically, it was

unclear whether the torque values specified in the design were insufficient, or whether procedural mistakes had been made in applying torque to the fasteners. Also, the failure to ensure that the P2M2s were properly machined cost the project some time and money to modify all eight units.

In spite of these challenges, the educational value afforded by the design and testing of the NPSCuL-Lite EDU cannot be overstated. As mentioned in Chapter I, one of the primary goals of any CubeSat program is education of the space workforce. The NPSCuL Team learned far more about spacecraft structural design and testing procedures from the failures, than they would have learned had the tests come off without a hitch. A case in point is the decision to continue the testing after the first failure. In hindsight, the tests might have been discontinued, and most of the lessons outlined in this chapter would have been revealed. But this decision yielded a wealth of experience in both structural design and program management. The second test taught the student team that neither cost nor schedule are paramount. The lessons learned were very important and will help to ensure success in the follow-on testing. For example, under the circumstances, no “on-the-spot” fix could change the fact that there was something wrong with the test conditions—the P-POD mating surfaces were not flat. In the end, the NPSCuL team verified that “simplicity of design” may be a good starting point, but that early structural and fastener analysis and proper test configurations are still important.

## B. RECOMMENDATIONS

### 1. Improvements to Vibration Testing Methods

To improve the overall quality of future vibration testing in support of NPSCuL-Lite and other NPS SSAG small satellite programs, three recommendations are provided below. First, the anomaly regarding the ability of the electrodynamic shakers to accurately produce the required environmental parameters across the test spectrum must be resolved. Second, accelerometer

mounting considerations should be considered as part of the design of space-related structures that will undergo vibration tests. The video record of each test proved invaluable to the post-test investigation, and should be considered a best practice. Finally, there is a substantial base of information available via industry websites that is available to test engineers who are unfamiliar with vibration test procedures and analysis.

As mentioned in Chapter III, an anomaly persisted throughout all vibration tests performed as part of this thesis: the shakers used were unable to properly control the tests in accordance with the operator specified test definitions. Between the P2M2 testing and the abbreviated testing of the NPSCuL-Lite EDU, many essential test methodologies changed. The NPSCuL-Lite EDU test used a different shaker, a better-designed shaker test fixture, different accelerometers, different accelerometer attachment methods, and had a highly experienced technician running the test; yet the same anomaly arose. Several possible reasons for this were suggested in Chapters II and III of this thesis. It is possible that the ABC qualification environment is too severe for the medium-range shakers used. Specifically, a larger shaker with a significantly more massive armature might be less susceptible to feedback from the dynamics of the article under test. Alternatively, it would have been advantageous to see if the control problem persisted when a test was performed using a slip table; the slip table adds mass to the control loop and might serve to isolate the control loop from the test article's motions. At a minimum, some detailed investigation should be conducted to answer the following questions:

- Is this anomaly a very common, or very uncommon, occurrence in the testing of spacecraft?
- Does this anomaly result in significant overtesting of the structure?
- What methods can be used to reduce the effect of this anomaly?

A second recommendation concerns the method of affixing accelerometers to a structure for testing purposes. Throughout this thesis work, accelerometers were affixed using various adhesives including tack wax, hot glue, and cyanoacrylate (super-glue). These methods are often chosen for convenience: they require no modification of the mounting surface and the accelerometer can be moved to alternate locations easily. There are two drawbacks to adhesive mounting of accelerometers. First, the accelerometers may fall off under high accelerations; this problem was encountered several times when tack wax was used to mount larger accelerometers. Hot glue and cyanoacrylate performed much better in this respect. The second issue is that adhesive mounting can interfere with accurate measurement, because the adhesives may isolate the accelerometer from the test article. This effect is more pronounced at higher frequencies and depends on the hardness of the adhesive, the thickness of the layer of adhesive, and the temperature at which testing is performed.[26]

The ideal method for mounting accelerometers on a test article is stud mounting. This requires a small, tapped hole to be drilled into the test article at the mounting position. The size of the hole depends on the accelerometer, and each accelerometer has either a male threaded feature that can be screwed directly into the test article, or a female threaded feature and a double-ended stud to make the connection. This "hard" connection provides the best frequency response performance. If adhesive mounting is required, cyanoacrylate is recommended; it provides good frequency response and it will form a very secure bond so long as the surfaces are clean. The only downside to this adhesive is that it may be necessary to use a solvent to remove the

26 "Primer: Measuring Vibration," Bruel & Kjaer, 1982, http://www.bksv.com/doc/br0094.pdf (accessed June 4, 2009).

accelerometer. If cyanoacrylate cannot be used, then a compromise must be made: hot glue provides a more secure bond than tack wax, but tack wax is less likely to influence the output of the accelerometer.[27]

As was briefly mentioned in Chapter III, a video camera was used to visually record each of the NPSCuL-Lite EDU vibration tests. This evidence proved invaluable during the post-test investigation; however, the camera did not record the failure during the second test because it was not in a good position. In the future, it is recommended that several cameras be available to view the article under test from several different angles. The SSAG has investigated purchasing an integrated closed-circuit TV system for this purpose; the value of such an investment cannot be overstressed.

Finally, the author came across a number of web-based resources, provided by major manufacturers of industrial test equipment that provided useful information and training regarding vibration testing. Many of the lessons learned in this thesis were learned the hard way, by trial and error. In order to avoid re-learning the same lessons the same way, anyone interested in conducting vibration testing who does not have access to formal training should take advantage of these resources. Typically, some kind of registration with the company is required to gain access to the instructional materials, but there is no fee and many items can be downloaded for future reference. The following websites were very useful: Endevco (www.endevco.com); Brüel & Kjær (www.bkhome.com); M+P International (www.mpihome.com); Kistler (www.kistler.com). For information about vibration loosening of fasteners, the author highly recommends the following tutorial from Bolt Science Limited: http://www.boltscience.com/pages/vibloose.htm. This tutorial includes a video and is an excellent introduction to fastener failure modes.

27 "Endevco Guide to Adhesively Mounting Accelerometers," Endevco, http://www.endevco.com/resources/tp_pdf/TP312.pdf (accessed June 4, 2009).

### 2. P2M2 and NPSCuL-Lite Design Modifications

It is clear that a number of design modifications are required prior to re-test of the NPSCuL-Lite EDU. The P2M2 design requires two improvements: flattening of the wall that faces NPSCuL-Lite, and amending the installation torque to set the proper preload for the center rod screws. NPSCuL-Lite itself requires a bit more. Additional analysis should be done with regard to the structure's dynamic mode shapes to minimize the bending of the walls. A complete fastener analysis must be performed. Additionally, the test and assembly procedures should be reviewed, and two suggestions for improvement will be presented here.

The P2M2 was designed to impose realistic loads on the NPSCuL-Lite structure during dynamic tests, at a fraction of the cost of a P-POD. The current design basically meets this objective. The flatness issue is the most serious concern, and it should be immediately addressed because the corrections will take a significant amount of time. The required flatness can be achieved in two ways. The simpler option would be to flatten the entire face, ensuring that there will be no gapping between the P2M2 and NPSCuL-Lite at installation. A more complex option would be to mill down (approximately .050 inches or so) the face everywhere except in the area where the screw thread inserts are installed. A real P-POD includes a feature at the LV structural interface which can be likened to two "rails"; the face of the P2M2 has sufficient material to allow milling that would create rails similar to the P-POD. These rails would then have to be precisely flattened, but this would provide a much more realistic interface with less likelihood of a problem due to gapping. Further, consideration should be given to using free-running screw thread inserts, vice locking inserts. In a telephone conference that was conducted as part of the post-test investigation, Cal Poly stated that, based on their experience with the P-POD, free running inserts are preferred not only because locking inserts don't provide any real benefit, but also because the locking features interfere with accurate torque measurement. Another possible area of concern would be the selection of

materials for the P2M2. While AL 6061 is relatively inexpensive, actual P-PODs are made of AL 7075, a stronger material. It is unclear whether the use of non-flight-similar materials was a contributing factor to the failure, but this question is worth some thought. Finally, the problem of screws backing out at the interfaces of the front and back plates with the center rod must be addressed. This problem was encountered during P2M2 standalone testing (above, Chapter II) and in the NPSCuL-Lite EDU testing (above, Chapter III). A fastener analysis should be conducted on these connections to maximize the preload on these screws. Consideration should be given to installing free running screw thread inserts into the holes in the center rod to make the connection stronger. While these changes will cost time and money, they can still be accomplished for orders of magnitude less expense than redesign or replacement with actual P-PODs.

As of this writing, some initial modeling has begun to try to modify the shape of the structure's first dynamic mode. The goal behind this is to find a way to minimize bending of the walls, which may have contributed to the failure of the fasteners connecting the P2M2s to NPSCuL-Lite. Any stiffening of the structure that results as consequence of this design change can only improve the overall performance of the system; but the main goal should be to eliminate wall bending, or at least shift any modes that cause wall bending to higher frequencies where they won't be able to deflect as severely. Since the degree to which this issue contributed to the failure is still largely unknown, this is probably the lowest priority in terms of design improvements and the resources of the NPSCuL-Lite program should be applied to this study accordingly. Any design change will result in significant expense to rework all of the design drawings and manufacture new parts. However, some of the components of the first NPSCuL EDU may not be reusable anyway.

A very brief introduction to fastener analysis was provided in Chapter III of this thesis. The conclusion was that applying insufficient preload will result in loss of preload and loosening of the fasteners to the point where other failures become more likely, regardless of whether locking mechanisms are employed. A

fastener failure has occurred when the joint is no longer stationary, not when the screw pulls out. Supplementary locking mechanisms serve merely as a backup to keep the screw in place for a certain amount of time. Understanding the load forces on the screws is the most difficult part of this process. Fortunately, ULA has offered some assistance with regard to this issue. Consideration must be given to using screws made of stronger materials with a higher yield strength, allowing the screws to accept more torque and thus more preload at installation. Attention must also be given to the pull-out strength of the parent material of the insert under higher preload conditions. Across most of the NPSCuL-Lite structure, there is little room for the addition of more fasteners; but this is not true of the NPSCuL-Lite/P2M2 interface. The addition of fasteners to this interface would distribute the dynamic loads among more fasteners, thus reducing the probability of fastener failure. Of course, any change in the number of fasteners requires buy-in from the P-POD manufacturer, Cal Poly. Finally, the fastener analysis must include a discussion of the use of various types of washers, and of the costs and benefits of counter-sunk flat-head screws.

Most structural dynamics tests, be they sine sweep, sine burst, or random vibration, involve some ramp-up time; typically they begin -12 dB to -6 dB below the target level of the test. This is done to detect and correct errors in assembly or anomalies caused by shipping or handling of the structure. Throughout the tests performed for this thesis, only visual examination was conducted between tests because it was felt that any tampering with the structure during testing might invalidate the test. However, it must be noted that the testing sequence itself creates situations that are unrealistic in terms of the actual environments experienced during launch. On an actual rocket launch, for example, the structure never experiences the full loading of the random vibration environment in only one axis; these loads are encountered simultaneously in all axes at once. So the questions arises: is it acceptable to re-tighten any loosened fasteners between tests? This could be done between the low-level vibration and the full qualification level, or concurrently with reconfiguring the test equipment for each

axis. The benefit of this addition to the assembly and test procedures would be improved performance in the test. This question should certainly be investigated further, and concurrence should be sought from the launch provider prior to the next qualification test.

In the post-test investigation, the remaining preload on the screws throughout the structure was evaluated by applying torque in the clockwise direction using a dial-type torque wrench. Because the screws had been marked to provide indication of whether a screw had turned, it was discovered that many of the screws that had not turned had still lost preload. It was further discovered that, when the specified torque value was once again attained, the screw had *turned past the point where specified torque had been reached the first time.* This phenomenon might be explained by embedment of the screws into the clearance holes or countersinks, but the initial visual inspection did not reveal any significant embedment. It is also possible that the act of subjecting the structure to random vibration, while the fasteners were insufficiently torqued for the random vibration environment, caused the various components to shift or settle. The result of this settling is that the mutual structural interference between the components is reduced, allowing the fasteners to snug up more closely against the structure. If this is true, as the evidence suggests, then it should be possible to use this behavior to the structure's advantage (provided an electrodynamic shaker were available at NPS during the NPSCuL-Lite construction timeframe). It would be relatively easy to secure all the fasteners to some fraction (perhaps 30%–50%, or more) of the specified final torque required, then perform a short duration random vibration of the empty structure to induce settling of the components and/or the screws. Following this vibration, the structural assembly could be completed by fully torquing each of the screws per the sequence outlined in the assembly procedure. The cost, in terms of time, to conduct this "production shake" would be insignificant compared to the cost of a fastener failure on NROL-41. It only remains to be determined to what level this shake should be performed, and for what duration. By carefully noting the

positions of the screw heads and the torque values applied to the screws before and after the “production shake,” it will be possible to at least qualitatively assess value of shaking the structure during production.

### 3. Future Integration Efforts in Support of NROL–41

As of June 2009, although none of the required ground support equipment for ADaMSat launch vehicle integration has been produced, much progress has been made on its design. This means that it may be difficult for alterations or improvements to these devices further down the road, so continued coordination with the launch provider regarding integration is essential. If the NPSCuL-Lite structure changes significantly, or if ADaMSat has any unique requirements with regard to ground support equipment, this will likely, impact ULA’s bottom line cost and schedule. Over and above what is required from ULA, several other ground support equipment designs must be addressed. With this in mind, an integrating contractor is needed immediately. The integrating contractor will be responsible for NPSCuL-Lite and all other ADaMSat components from the time they arrive at the ADaMSat integration site until the day of launch. Development and procurement of the items identified below will therefore be the responsibility of the integrating contractor, with assistance from all other parties involved. As evidenced by the coordination between the NPSCuL Team and ULA regarding ULA-procured ground support equipment, early and continued cooperation is the only way to ensure a successful design.

The development of a suitable shipping container for ADaMSat needs to begin promptly. There is no reason why the same container cannot be used for both the NPSCuL-Lite structure, and the fully integrated ADaMSat; but the requirements for ADaMSat will be driven by more than just the mass and volume of the payload. The NPSCuL-Lite structure is sensitive only to transportation loads, but the P-POD is not a sealed container, and the CubeSats within them will be sensitive to humidity, temperature, and the electromagnetic environment

during transport. The shipping container must therefore protect ADaMSat against all of these environments. Coordination with NPS, the sequencer provider, Cal Poly, and the CubeSat developers is essential.

The current operations plan for integration at the launch site requires a breakover fixture, because ADaMSat is expected to be shipped in the vertical but must be integrated in the horizontal. This thesis identified the GAS dolly as a possible solution, but ultimately the integration contractor will procure this equipment. Ideally, the breakover fixture would be an integral part of the shipping container, so that the breakover function could be performed as part of the unpacking process. The need for a vertical lift solution remains as an additional open item to be addressed by the integrating contractor; experience has shown that manual lift is possible, but this is not expressly recommended.

ADaMSat will spend a considerable amount of time (at least four months) stacked on the launch vehicle prior to launch. During this time, the Centaur will be in a controlled environment with regard to temperature and personnel access. But the technical interchange meeting at Vandenberg Air Force Base, in May of 2009, addressed several concerns regarding protection from other environmental conditions. It was suggested that a protective cover be created to shield ADaMSat from salt fog, humidity, and stray electromagnetic interference. This cover would also serve as a procedural interference measure to protect the payload from casual contact by personnel working in the vicinity of the Centaur aft bulkhead. Various forms of polyester film (PET) are available commercially that would likely meet these requirements, or a hard cover could be devised. At the technical interchange meeting, all parties agreed that a protective cover could be used as long as it was possible to remove and reinstall it several times; a line item would be included in the launch preparation sequence to remove the cover for the last time. To date, this device remains in the conceptual stage; but the NPSCuL program will certainly be involved in any work concerning environmental protection of the payload from delivery to the launch site, to delivery on orbit.

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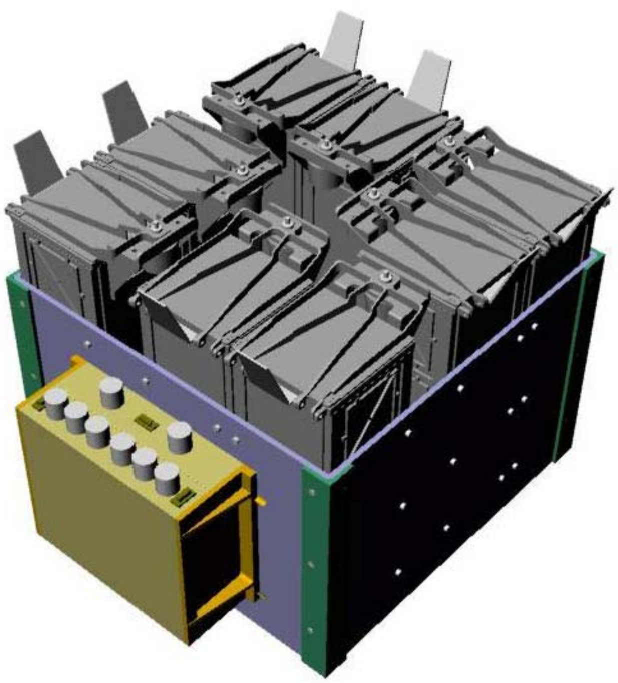
# APPENDIX

**Naval Postgraduate School CubeSat Launcher-Lite (NPSCuL-Lite)**
**Engineering Development Unit (EDU) Test Plan**

**12 May 2009**

**-- FINAL --**



Naval Postgraduate School
Space Systems Academic Group

777 Dyer Rd., Bldg. 233
Code (SP/Sd)
Monterey, CA 93943

## 1. INTRODUCTION

This document defines the test plan for structural verification of the Naval Postgraduate School CubeSat Launcher- Lite (NPSCuL-Lite) engineering development unit (EDU). The NPSCuL-Lite EDU will be tested to qualification levels, and is thus the structural qualification unit. The NPSCuL-Lite is a 170 lbs [77.1 kg], cuboid spacecraft with overall dimensions of approximately 20 in. [51 cm] width, 20 in. [51 cm] length, and 15 in. [38cm] height. Figure 1 shows the overall dimensions of the NPSCuL-Lite space vehicle along with the launch carrier coordinate system. NPSCuL-Lite, designed for the Aft Bulkhead Carrier of the ATLAS V (400 and 500 series) includes a mounting ring approximately 2.1 in. [5.3 cm] in height. NPSCuL-Lite will attach to the launch vehicle via the Aft Bulkhead Carrier which sits below the Evolved Expendable Launch Vehicles (EELV) Centaur upper stage. NPSCuL/-Lite may also be integrated on other launch vehicles via the EELV Secondary Payload Adapter (ESPA) or compatible interfaces.

NPSCuL-Lite is a low-cost, experimental spacecraft. That is, it is a Class D spacecraft per DOD-HDBK-343 classification guidelines[1]. Although a Class D spacecraft may follow a 'protoflight' testing path for reduced cost, NPSCuL-Lite will be tested using the EDU for qualification, and a separate flight unit will be tested to acceptance levels. The NPSCuL-Lite EDU will be dimensionally similar to the flight vehicle structure with dummy masses placed where subsystems (P-PODs and Sequencer unit) are to be located on the flight vehicle. The suite of tests within the scope of this document includes quasi-static loads testing and random vibration testing.

### 1.1 ABOUT THE NPSCUL P-POD MASS MODELS

NPSCuL P-POD mass models (P2M2) are intended for use ONLY in the qualification and acceptance testing of NPSCuL and NPSCuL-Lite structures. While the volume and inertial properties are similar to those of an actual, pre-deployment P-POD (as outlined in the P-POD MKIII ICD), the total mass may not be representative of any individual, flight-ready P-POD.

The P2M2 was designed to meet three major requirements: mass, center-of-gravity, and volume. Mass and center-of-gravity are factors that drive the modal characteristics and static/dynamic forces exerted by a P-POD on the NPSCuL/NPSCuL-Lite structure in the launch environment. Therefore these were the primary concern. The P2M2 is further designed to simulate the volume of the P-POD because the volume constraints of NPSCuL-Lite allow little clearance between P-PODs. By creating a physical model of nearly identical dimensions, the NPSCuL development team was able

[1] *Design, Construction, and Testing Requirements for One of a Kind Space Equipment,* DOD-HDBK-343, Sect. 3.1, Feb. 1, 1986.

to a) verify the P-PODs have sufficient clearance in the dynamic environment and b) verify and practice the integration sequence for NPSCuL, P-PODs, sequencer electronics, wiring harness, and the launch vehicle.

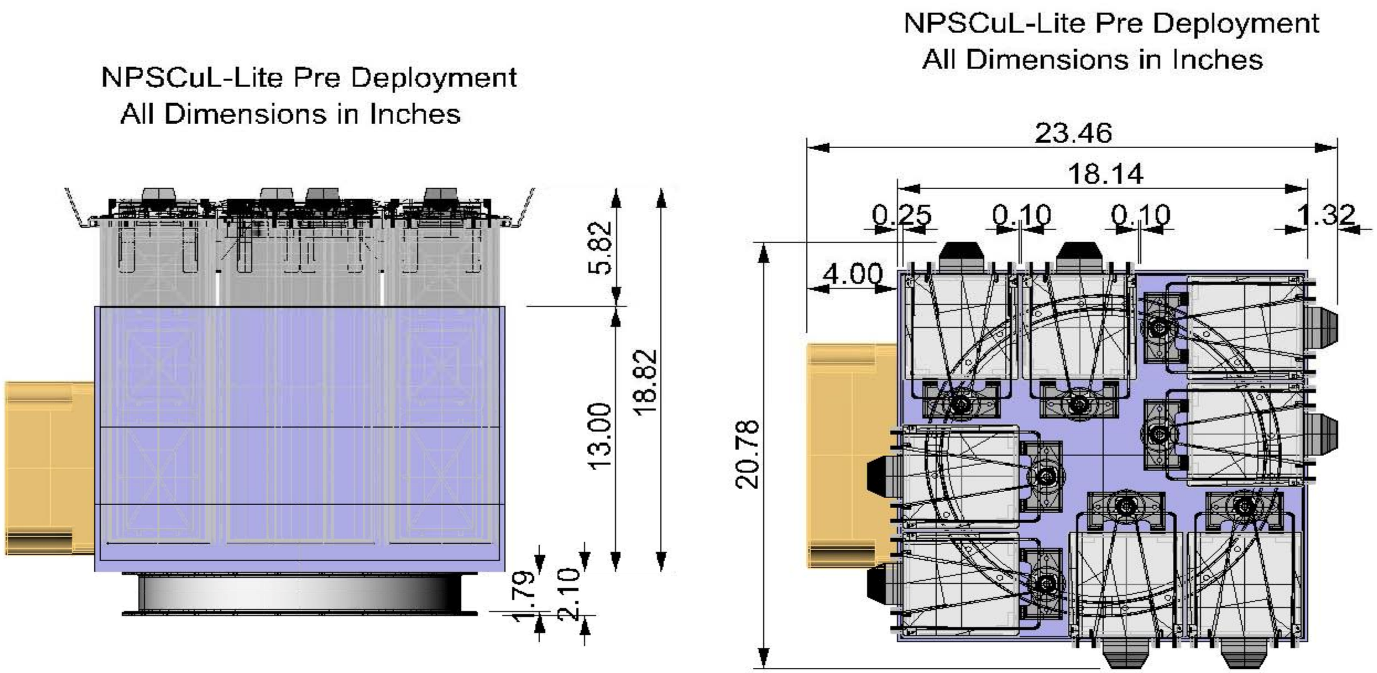



Figure 1. NPSCuL-Lite Overall Dimensions.

## 2. TEST FLOW

The NPSCuL-Lite EDU suite of tests is exclusively for the purposes of structural integrity verification. Therefore, no functional testing is performed, and only brief data analysis of the tests will be performed following each test to ensure that no damage has occurred to the load-bearing structure. Data recorded during the test will be post-processed by the NPSCuL Program Office (at NPS) following completion of testing. The EDU structure will be tested in each of the three axes for each environmental test. Prior to each test a low-level sine sweep will be performed to measure the natural frequencies of the structure in its test/launch/pre-deployment configuration. This data will be used not only to verify the fundamental frequency of the spacecraft in its launch configuration, but also to verify that between each test the dynamics of the structure have not significantly changed which could indicate a failure or anomaly. Figure 2 shows the test flow.

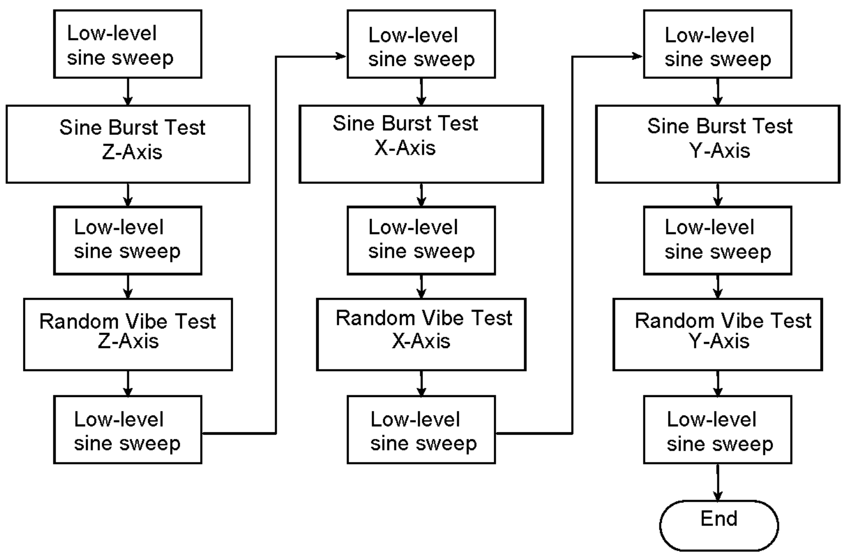



Figure 2. Test Flow.

## 3. TEST DESCRIPTIONS

The NPSCuL-Lite EDU will be attached to a shaker system for each of the qualification tests. For each test, closed-loop vibration control shall be implemented to ensure that the force inputs are within specification. Also for each test, the testing sequence shall start at –12 dB of the target level, and step up incrementally to the target level.

### 3.1. Low-level Sine Sweep

The sine sweep test, "survey test," will start from 15 Hz and end at 480 Hz at a rate of 2 octaves per minute. Two sweeps will be performed. One sweep will be in the ascending frequency direction (up), and the one sweep will be descending (down). One measurement of the sweep will be recorded for each sweep yielding two measurements per test. Each measurement will be plotted in acceleration (g) vs. frequency (Hz). Accelerations for the sweep at any time may not exceed 0.25 g. The following table summarizes the sine sweep parameters.

Table 1. Sine Sweep Test Parameters.

| Description | Parameter Value |
|---|---|
| Frequency Range | 15 Hz - 2000 Hz |
| Acceleration | 0.25 g (max.) |
| Sweep Rate | 4 Octaves/min. |
| No. of sweeps | 1 up + 1 down = 2 total |
| Measurements | 1 per sweep (frequency spectrum) for each channel (control and measurement) |
| Processed data | 1 FRF for each measurement channel per sweep |

### 3.2. Static Loads Test

The static loads test will be performed by a fixed and low frequency (25 Hz) sine-burst test on the spacecraft structure such that quasi-static loads are applied to the structure to levels of root-sum-square of the limit loads (given in the ABC User's Guide, 3.2.1) plus a factor of safety of +1.25. The test must achieve a minimum of 5 cycles at full level per axis[2]. Testing to failure will not be performed. Instrumentation will placed similarly to the sine sweep test placement.

[2] Reference NASA GSFC-STD-7000 (formerly NASA GEVS) Table 2.2-2. This document is used as an industry standard practice pending additional guidance from the launch vehicle provider.

Table 2. Sine Burst (Quasi-Static) Test Parameters.

| ABC Secondary Payload Limit Loads | | | | | | | |
|---|---|---|---|---|---|---|---|
| Limit Load (g) | | | Root Sum Square (g) | Factor of Safety | Test Load (g) | | |
| X | Y | Z | | | X (FSx) | Y (FSy) | Z (FSz) |
| 5.0 | 5.0 | 7.0 | 9.9 | 1.25 | 12.44 | 12.44 | 12.44 |

### 3.3. Random Vibration Test

The random vibration test is to be performed in each axis, (X, Y, and Z). The coordinate system is given in Figure 1. The test specification for NPSCuL-Lite comprises the maximum predicted environment (MPE) for NPSCuL-Lite. Random vibration testing levels for this EDU structure shall be 6 dB above the MPE spectrum and shall have a duration of three minutes at the target level for each axis in accordance with ABC User's Guide. Figure 3 shows the spectrum to which testing is to be performed for all three axes; information is given in more detail in Table 2.

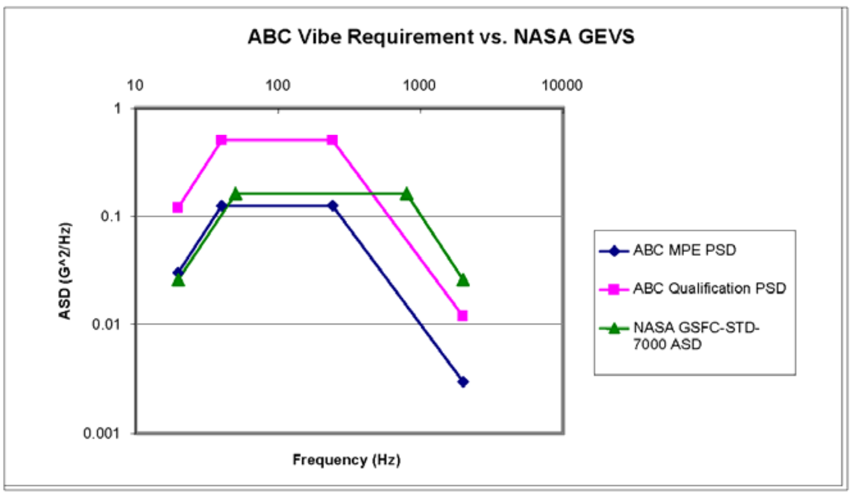



Figure 3. Random Vibration Acceleration Spectral Density (ASD).

Table 2. NPSCuL Acceleration Spectral Density for EDU Test (+6dB; 15.2 $G_{rms}$).

| Frequency | NPSCuL EDU Test Criterion ($g^2$/Hz) | dB/Octave |
|---|---|---|
| 20 | 0.12 | 6.021 |
| 40 | 0.5 | 0.00 |
| 240 | 0.5 | -6.021 |
| 2000 | 0.012 | |

*Test duration at target level is 3 minutes.

Prior to, and following, each random vibration test, a low-level sine sweep (see Table 1) of not greater than 0.25 g is to be performed between the range of 15 Hz and 2000 Hz at no greater than 2 Octaves per minute in both directions (one sweep up and one sweep down) with measurements taken for each sweep (frequency spectrum). The test schedule for random vibration is at the discretion of the test operator, but shall begin at not higher than –12 dB of the target test level and shall proceed in increments not to exceed 3 dB between level changes. Closed-loop vibration control shall be used for all vibration testing. Measurement points are required on the spacecraft structure identical to the other testing (sine burst and sine sweep) as defined in section 4. Each measurement point requires either single-axis or tri-axial accelerometers. Accelerometers shall be mounted using tack wax to ensure that no damage will occur to the material finish or coating. Measurements shall be taken at the target level for all measurement channels and control channels. Following reconfiguration of the EDU and the test equipment (for each test axis) another low-level sine sweep shall be performed with measurements taken as in previous sine sweep tests.

## 4. INSTRUMENTATION AND MEASUREMENTS

NPSCuL-Lite shall be instrumented with accelerometers to record the acceleration input to the structure and the structural response in acceleration. Figure 4 shows the placement of instrumentation. Precise location of the transducers shall be provided with tolerance of ±0.25 inch. Once installed, a (digital) photographic record shall be taken to show the installed locations. One single-axis accelerometer shall be installed on the base plate bottom, in the test axis on the adapter ring. One tri-axial accelerometer shall be mounted on the sequencer to measure generic accelerations of the flight electronics housing. Three single-axis accelerometers shall be installed on the walls to measure maximum acceleration of each wall. Three single-axis accelerometers shall be installed on a corner-mounted P2M2 to measure generic accelerations of a P-POD. Control accelerometer measurements for closed-loop vibration control shall also be recorded as part of the test data for the NPSCuL-Lite EDU testing. One control accelerometer is required, and calibration data shall be provided as part of the test data, e.g., transducer sensitivity in Volts (or millivolts) per g.

Table 3 shows a summary of the measurement requirements and applicable data. Actual channel numbers are at the operator's discretion.

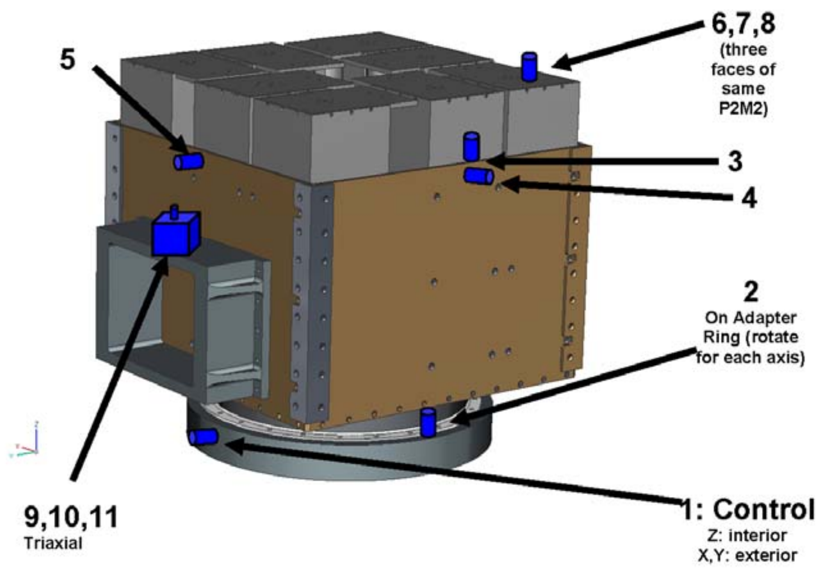



Figure 4. Instrumentation Placement on NPSCuL-Lite EDU.

Table 3. Instrumentation and Measurement Summary.

| Transducer Channel | Description | Required Data* | | |
|---|---|---|---|---|
| | | Sine Sweep | Sine Burst | Random Vibration |
| 2 | Single-axis accelerometer, in-line with test axis, on adapter ring | • Acceleration (g/Hz)<br>• Frequency response spectrum referenced to control accelerometer | | • Acceleration spectral density ($g^2$/Hz)<br>• Frequency response spectrum referenced to control accelerometer |
| 3,4,5 | Single-axis accelerometers, [X, Y, Z] directions, Walls 1 and 4 | • Acceleration (g/Hz)<br>• Frequency response spectrum referenced to control accelerometer | | • Acceleration spectral density ($g^2$/Hz)<br>• Frequency response spectrum referenced to control accelerometer |
| 6,7,8 | Single-axis accelerometers, [X, Y, Z] directions, corner-mounted P2M2 | • Acceleration (g/Hz)<br>• Frequency response spectrum referenced to control accelerometer | | • Acceleration spectral density ($g^2$/Hz)<br>• Frequency response spectrum referenced to control accelerometer |
| 9,10,11 | Triaxial accelerometer, [X, Y, Z] directions, sequencer housing | • Acceleration (g/Hz)<br>• Frequency response spectrum referenced to control accelerometer | | • Acceleration spectral density ($g^2$/Hz)<br>• Frequency response spectrum referenced to control accelerometer |
| 1 (Control Channel) | Accelerometer mounted on test fixture; used for closed-loop vibration control | • Acceleration (g/Hz) | | • Acceleration spectral density ($g^2$/Hz) |

* Data shall include transducer calibration information (sensitivity), locations of installation, and photographic records.

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